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PCT/EP2004/013042

19.01.05

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PCT/EP2004/013042
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# PCT

## REQUEST

The undersigned requests that the present international application be processed according to the Patent Cooperation Treaty.

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PCT/IT 03/00742

International Application No.

17 NOV 2003 17/11/03

International Filing Date

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Name of receiving Office and "PCT International Application"

Applicant's or agent's file reference (if desired) (12 characters maximum) ML00H1-1/P-WO

MINISTERO DELLE ATTIVITA' ... 11,00 Euro

**Box No. I TITLE OF INVENTION**

Free space optical communications

**Box No. II APPLICANT** ☐ This person is also inventor

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

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Applicant's registration No. with the Office

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This person is applicant for the purposes of: ☐ all designated States ☒ all designated States except the United States of America ☐ the United States of America only ☐ the States indicated in the Supplemental Box

**Box No. III FURTHER APPLICANT(S) AND/OR (FURTHER) INVENTOR(S)**

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

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This person is:
☐ applicant only
☒ applicant and inventor
☐ inventor only *(If this check-box is marked, do not fill in below.)*

Applicant's registration No. with the Office

State *(that is, country)* of nationality: IT

State *(that is, country)* of residence: IT

This person is applicant for the purposes of: ☐ all designated States ☐ all designated States except the United States of America ☒ the United States of America only ☐ the States indicated in the Supplemental Box

☒ Further applicants and/or (further) inventors are indicated on a continuation sheet.

**Box No. IV AGENT OR COMMON REPRESENTATIVE; ~~OR ADDRESS FOR CORRESPONDENCE~~**

The person identified below is hereby/has been appointed to act on behalf of the applicant(s) before the competent International Authorities as: ☒ agent ☐ common representative

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country.)*

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☐ **Address for correspondence:** Mark this check-box where no agent or common representative is/has been appointed and the space above is used instead to indicate a special address to which correspondence should be sent.

Form PCT/RO/101 (first sheet) (March 2001; reprint July 2003) *See Notes to the request form*

PCT/IT 03/00742

Sheet No. ...2..

**Continuation of Box No. III FURTHER APPLICANT(S) AND/OR (FURTHER) INVENTOR(S)**

*If none of the following sub-boxes is used, this sheet should not be included in the request.*

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This person is:
- [ ] applicant only
- [x] applicant and inventor
- [ ] inventor only *(If this check-box is marked, do not fill in below.)*

Applicant's registration No. with the Office

State *(that is, country)* of nationality: IT

State *(that is, country)* of residence: IT

This person is applicant for the purposes of: [ ] all designated States [ ] all designated States except the United States of America [x] the United States of America only [ ] the States indicated in the Supplemental Box

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

This person is:
- [ ] applicant only
- [ ] applicant and inventor
- [ ] inventor only *(If this check-box is marked, do not fill in below.)*

Applicant's registration No. with the Office

State *(that is, country)* of nationality:

State *(that is, country)* of residence:

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Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

This person is:
- [ ] applicant only
- [ ] applicant and inventor
- [ ] inventor only *(If this check-box is marked, do not fill in below.)*

Applicant's registration No. with the Office

State *(that is, country)* of nationality:

State *(that is, country)* of residence:

This person is applicant for the purposes of: [ ] all designated States [ ] all designated States except the United States of America [ ] the United States of America only [ ] the States indicated in the Supplemental Box

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

This person is:
- [ ] applicant only
- [ ] applicant and inventor
- [ ] inventor only *(If this check-box is marked, do not fill in below.)*

Applicant's registration No. with the Office

State *(that is, country)* of nationality:

State *(that is, country)* of residence:

This person is applicant for the purposes of: [ ] all designated States [ ] all designated States except the United States of America [ ] the United States of America only [ ] the States indicated in the Supplemental Box

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Sheet No. ...3...

**Box No. V DESIGNATION OF STATES** *Mark the applicable check-boxes below; at least one must be marked.*

The following designations are hereby made under Rule 4.9(a):

**Regional Patent**

☒ AP **ARIPO Patent:** GH Ghana, GM Gambia, KE Kenya, LS Lesotho, MW Malawi, MZ Mozambique, SD Sudan, SL Sierra Leone, SZ Swaziland, TZ United Republic of Tanzania, UG Uganda, ZM Zambia, ZW Zimbabwe, and any other State which is a Contracting State of the Harare Protocol and of the PCT *(if other kind of protection or treatment desired, specify on dotted line)* ..........

☒ EA **Eurasian Patent:** AM Armenia, AZ Azerbaijan, BY Belarus, KG Kyrgyzstan, KZ Kazakhstan, MD Republic of Moldova, RU Russian Federation, TJ Tajikistan, TM Turkmenistan, and any other State which is a Contracting State of the Eurasian Patent Convention and of the PCT

☒ EP **European Patent:** AT Austria, BE Belgium, BG Bulgaria, CH & LI Switzerland and Liechtenstein, CY Cyprus, CZ Czech Republic, DE Germany, DK Denmark, EE Estonia, ES Spain, FI Finland, FR France, GB United Kingdom, GR Greece, HU Hungary, IE Ireland, IT Italy, LU Luxembourg, MC Monaco, NL Netherlands, PT Portugal, RO Romania, SE Sweden, SI Slovenia, SK Slovakia, TR Turkey, and any other State which is a Contracting State of the European Patent Convention and of the PCT

☒ OA **OAPI Patent:** BF Burkina Faso, BJ Benin, CF Central African Republic, CG Congo, CI Côte d'Ivoire, CM Cameroon, GA Gabon, GN Guinea, GQ Equatorial Guinea, GW Guinea-Bissau, ML Mali, MR Mauritania, NE Niger, SN Senegal, TD Chad, TG Togo, and any other State which is a member State of OAPI and a Contracting State of the PCT *(if other kind of protection or treatment desired, specify on dotted line)* ..........

**National Patent** *(if other kind of protection or treatment desired, specify on dotted line):*

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☒ AL Albania ..........
☒ AM Armenia ..........
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☒ AU Australia ..........
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☒ TT Trinidad and Tobago ..........
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☒ TZ United Republic of Tanzania
☒ UA Ukraine ..........
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☒ US United States of America ..........
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☒ UZ Uzbekistan ..........
☒ VC Saint Vincent and the Grenadines
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**Precautionary Designation Statement:** In addition to the designations made above, the applicant also makes under Rule 4.9(b) all other designations which would be permitted under the PCT except any designation(s) indicated in the Supplemental Box as being excluded from the scope of this statement. The applicant declares that those additional designations are subject to confirmation and that any designation which is not confirmed before the expiration of 15 months from the priority date is to be regarded as withdrawn by the applicant at the expiration of that time limit. *(Confirmation (including fees) must reach the receiving Office within the 15-month time limit.)*

PCT/IT 03/00742

Sheet No. ..4...

**Box No. VI PRIORITY CLAIM**

The priority of the following earlier application(s) is hereby claimed:

| Filing date of earlier application *(day/month/year)* | Number of earlier application | Where earlier application is: national application: country or Member of WTO | regional application:* regional Office | international application: receiving Office |
|---|---|---|---|---|
| item (1) | | | | |
| item (2) | | | | |
| item (3) | | | | |
| item (4) | | | | |
| item (5) | | | | |

☐ Further priority claims are indicated in the Supplemental Box.

The receiving Office is requested to prepare and transmit to the International Bureau a certified copy of the earlier application(s) *(only if the earlier application was filed with the Office which for the purposes of this international application is the receiving Office)* identified above as:

☐ all items ☐ item (1) ☐ item (2) ☐ item (3) ☐ item (4) ☐ item (5) ☐ other, see Supplemental Box

* *Where the earlier application is an ARIPO application, indicate at least one country party to the Paris Convention for the Protection of Industrial Property or one Member of the World Trade Organization for which that earlier application was filed (Rule 4.10(b)(ii)):* ..........

**Box No. VII INTERNATIONAL SEARCHING AUTHORITY**

**Choice of International Searching Authority (ISA)** *(if two or more International Searching Authorities are competent to carry out the international search, indicate the Authority chosen; the two-letter code may be used)*:

ISA / EP

**Request to use results of earlier search; reference to that search** *(if an earlier search has been carried out by or requested from the International Searching Authority)*:

Date *(day/month/year)* Number Country *(or regional Office)*

**Box No. VIII DECLARATIONS**

The following declarations are contained in Boxes Nos. VIII (i) to (v) *(mark the applicable check-boxes below and indicate in the right column the number of each type of declaration)*: Number of declarations

☐ Box No. VIII (i) Declaration as to the identity of the inventor :

☐ Box No. VIII (ii) Declaration as to the applicant's entitlement, as at the international filing date, to apply for and be granted a patent :

☐ Box No. VIII (iii) Declaration as to the applicant's entitlement, as at the international filing date, to claim the priority of the earlier application :

☐ Box No. VIII (iv) Declaration of inventorship (only for the purposes of the designation of the United States of America) :

☐ Box No. VIII (v) Declaration as to non-prejudicial disclosures or exceptions to lack of novelty :

**Box No. IX CHECK LIST; LANGUAGE OF FILING**

This international application contains:

(a) in paper form, the following number of sheets:

| | | |
|---|---|---|
| request (including declaration sheets) | : | 5 |
| description (excluding sequence listings and/or tables related thereto) | : | 34 35 |
| claims | : | 2 |
| abstract | : | 1 |
| drawings | : | 20 |
| Sub-total number of sheets | : | 62 [63] |
| sequence listings | : | |
| tables related thereto | : | |
| *(for both, actual number of sheets if filed in paper form, whether or not also filed in computer readable form; see (c) below)* | | |
| Total number of sheets | : | 62 [63] |

(b) ☐ only in computer readable form (Section 801(a)(i))
- (i) ☐ sequence listings
- (ii) ☐ tables related thereto

(c) ☐ also in computer readable form (Section 801(a)(ii))
- (i) ☐ sequence listings
- (ii) ☐ tables related thereto

Type and number of carriers (diskette, CD-ROM, CD-R or other) on which are contained the
- ☐ sequence listings: .................
- ☐ tables related thereto: ............

*(additional copies to be indicated under items 9(ii) and/or 10(ii), in right column)*

This international application is accompanied by the following item(s) *(mark the applicable check-boxes below and indicate in right column the number of each item)*: Number of items

1. ☐ fee calculation sheet :
2. ☐ original separate power of attorney :
3. ☐ original general power of attorney :
4. ☐ copy of general power of attorney; reference number, if any: ........ :
5. ☐ statement explaining lack of signature :
6. ☐ priority document(s) identified in Box No. VI as item(s): ........ :
7. ☐ translation of international application into *(language)*: ........ :
8. ☐ separate indications concerning deposited microorganism or other biological material :
9. ☐ sequence listings in computer readable form *(indicate type and number of carriers)*
   - (i) ☐ copy submitted for the purposes of international search under Rule 13*ter* only (and not as part of the international application) :
   - (ii) ☐ *(only where check-box (b)(i) or (c)(i) is marked in left column)* additional copies including, where applicable, the copy for the purposes of international search under Rule 13*ter* :
   - (iii) ☐ together with relevant statement as to the identity of the copy or copies with the sequence listings mentioned in left column :
10. ☐ tables in computer readable form related to sequence listings *(indicate type and number of carriers)*
    - (i) ☐ copy submitted for the purposes of international search under Section 802(b-*quater*) only (and not as part of the international application) :
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11. ☐ other *(specify)*: ........ :

Figure of the drawings which should accompany the abstract: 1

Language of filing of the international application: English

**Box No. X SIGNATURE OF APPLICANT, AGENT OR COMMON REPRESENTATIVE**

*Next to each signature, indicate the name of the person signing and the capacity in which the person signs (if such capacity is not obvious from reading the request).*

Massimo Tavella

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1. Date of actual receipt of the purported international application: 17 NOV. 2003 17/11/03
2. Drawings: ☒ received: ☐ not received:
3. Corrected date of actual receipt due to later but timely received papers or drawings completing the purported international application:
4. Date of timely receipt of the required corrections under PCT Article 11(2):
5. International Searching Authority (if two or more are competent): ISA /
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Sheet No. ...5...

**Box No. IX CHECK LIST; LANGUAGE OF FILING**

This international application contains:

(a) in paper form, the following number of sheets:

| | | |
|---|---|---|
| request (including declaration sheets) | : | 5 |
| description (excluding sequence listings and/or tables related thereto) | : | ~~35~~ 34 A |
| claims | : | 2 |
| abstract | : | 1 |
| drawings | : | 20 |
| **Sub-total number of sheets** | : | ~~63~~ 62 A |
| sequence listings | : | |
| tables related thereto | : | |

*(for both, actual number of sheets if filed in paper form, whether or not also filed in computer readable form; see (c) below)*

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|---|---|---|
| **Total number of sheets** | : | ~~63~~ 62 A |

4/10

(b) ☐ **only in computer readable form** (Section 801(a)(i))
- (i) ☐ sequence listings
- (ii) ☐ tables related thereto

(c) ☐ **also in computer readable form** (Section 801(a)(ii))
- (i) ☐ sequence listings
- (ii) ☐ tables related thereto

Type and number of carriers (diskette, CD-ROM, CD-R or other) on which are contained the
- ☐ sequence listings: ..................
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This international application is accompanied by the following item(s) *(mark the applicable check-boxes below and indicate in right column the number of each item)*: — Number of items

1. ☐ fee calculation sheet :
2. ☐ original separate power of attorney :
3. ☐ original general power of attorney :
4. ☐ copy of general power of attorney; reference number, if any: .................... :
5. ☐ statement explaining lack of signature :
6. ☐ priority document(s) identified in Box No. VI as item(s): .................... :
7. ☐ translation of international application into *(language)*: .................... :
8. ☐ separate indications concerning deposited microorganism or other biological material :
9. ☐ sequence listings in computer readable form *(indicate type and number of carriers)*
   - (i) ☐ copy submitted for the purposes of international search under Rule 13*ter* only (and not as part of the international application) :
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10. ☐ tables in computer readable form related to sequence listings *(indicate type and number of carriers)*
    - (i) ☐ copy submitted for the purposes of international search under Section 802(b-*quater*) only (and not as part of the international application) :
    - (ii) ☐ *(only where check-box (b)(ii) or (c)(ii) is marked in left column)* additional copies including, where applicable, the copy for the purposes of international search under Section 802(b-*quater*) :
    - (iii) ☐ together with relevant statement as to the identity of the copy or copies with the tables mentioned in left column :
11. ☐ other *(specify)*: .................... :

**Figure of the drawings which should accompany the abstract:** 1

**Language of filing of the international application:** English

**Box No. X SIGNATURE OF APPLICANT, AGENT OR COMMON REPRESENTATIVE**

*Next to each signature, indicate the name of the person signing and the capacity in which the person signs (if such capacity is not obvious from reading the request).*

Massimo Tavella

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| 1. Date of actual receipt of the purported international application: 17 NOV 2003 17/11/03 | 2. Drawings: ☒ received: ☐ not received: |
| 3. Corrected date of actual receipt due to later but timely received papers or drawings completing the purported international application: | |
| 4. Date of timely receipt of the required corrections under PCT Article 11(2): | |
| 5. International Searching Authority (if two or more are competent): ISA / — 6. ☐ Transmittal of search copy delayed until search fee is paid | |

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Applicant: Media Lario s.r.L.
Attorney's ref. ML00H11/P-WO

**Free space optical communications**

The present invention relates to optical communications, and more particularly relates to high bandwidth free space optical communications.

The increased need for high bandwidth (high data rate) communication links induced by the recent growth of the internet and mobile communications has led to renewed interest in free space optical communication (Whipple, "Free space communications connects", Photonics at work, October 1999). In free space optical communications the data are transmitted through a communication link between a transmitting station and a receiving station by a laser beam preferably having a wavelength of about 1550 nm without using a physical medium such as an optical fibre or the like. Depending on the weather conditions, communications links over a distance of several kilometres with a bandwidth of up to 2.5Gbits per second have been demonstrated (P.F. Szajowski et al., "Key elements of high speed WTM terrestrial free space optical communication systems", SPIE paper no. 3932-01). Such free space optical telecommunications links are especially useful for connecting facilities having high data transmission needs with one another, such as banks and universities in metropolitan areas. Another possible application is the high bandwidth live broadcasting of sports events, where an optical free space communication link can be set up temporarily at low cost.

In order to avoid health risks associated with laser radiation, the laser power has to be low (a few milliwatts) and the beam diameter must be large (about several tens of centimetres). To establish an optical free space communication link, the optical signal therefore has to be coupled out of an optical fibre network and directed with a transmission telescope over the desired distance directly to the receiving telescope where the received beam has to be concentrated and coupled into another optical network.

Various aspects of optical free space communication systems have been described. For example, EP-A-1,152,555 discloses electroforming replication techniques for the fabrication of optical mirror elements for high bandwidth free space optical communication. In addition, EP-A-1,172,949 discloses a free space optical communication system comprising a first unit having a first transmitter and a first receiver and a second unit having a second receiver corresponding to the first transmitter and a second transmitter corresponding to the first receiver, wherein the first and second transmitter and the first and second receiver comprise a reflective optical telescope, and optical fibre positioned in the focal region of the reflective optical telescope, and a positioning unit for moving the optical fibre in the direction of the optical axis of the telescope and within a plane perpendicular thereto. The unit is mounted on a tip-tilt positioning system electronically controlled (gimbal). This system provides an optical tracking function allowing a stable, secure, and high-bandwidth optical communication link.

US-B-6,411,414 discloses an optical wireless link using wavelength division multiplexing. And EP-A-0,977,070 discloses an optical telescope with a shared (Tx/Rx) optical path in an optical communications terminal; however, a separate link is provided, taking the beacon signal from the secondary (dichroic) mirror.

Furthermore, a problem with available free space optical communication systems is a lack of power or redundancy in the signalling, making communications more vulnerable to atmospheric conditions. Also, the systems advanced heretofore also tend to involve complex optical arrangements for handling signals.

There is a need for optical communications terminals and communications systems that overcome the aforementioned problems and provide an improved performance. There is a need for terminals having optical systems of reduced complexity and component weight, so as to greater facilitate usage in diverse environments (e.g. aircraft- or satellite-borne, as well as ground-based).

The present invention provides an optical communications terminal, comprising: an optical telescope; a transmitter unit including at least one transmitter coupled to source of optical signals; a receiver unit for receiving optical signals; an optical system defining a transmit optical path between the optical telescope and the transmitter unit, and defining a receive optical path between the optical telescope and the receiver unit; and a beacon detector for detecting beacon optical signals received at the optical telescope; characterised in that a beacon optical path between the optical telescope and the beacon detector comprises at least a portion of said transmit optical path and/or said receive optical path.

Preferably, the transmitter unit, receiver unit and beacon detector are disposed at or adjacent the focal plane of the optical telescope.

In one embodiment: the system, the optical system includes a relay lens and a first mirror, and the optical path between said first mirror and the optical telescope is common to the transmit optical path, the receive optical path and the beacon optical path. The optical system may include a beamsplitter between the first

mirror and the receiver unit, the beamsplitter, in use, passing receiver optical signals along the transmit optical path to the receiver unit and reflecting beacon optical signals along the beacon optical path to the beacon.

Preferably, the transmitter unit includes a plurality of transmitters.

Preferably, for the or each transmitter an aperture is provided in the first mirror, a separate transmit optical path thereby being provided from the or each transmitter to the optical telescope via a respective aperture. Preferably, the or each transmitter comprises the terminating portion of a single mode optical fibre, a collimating lens preferably being provided at said terminating portion in a respective transmit optical path. In the case of a plurality of transmitters, each transmitter may be fed by the same optical signal, or may be fed by a different optical signal. In one embodiment, there are three transmitters.

Preferably, the beacon optical path includes a second focussing lens between said beamsplitter and the beacon detector. Preferably, the beacon optical path includes a filter system between said second focussing lens and the beam detector, the filter system preferably including, in sequence, a filter passing a first predetermined frequency and a neutral density filter. The first predetermined frequency is, for example, 830nm.

Preferably, the receiver unit includes one receiver for receiving optical signals at a second predetermined frequency, different to said first predetermined frequency, said second predetermined frequency preferably being 1150 nm. The receiver may comprise a terminating portion of a multimode optical fibre.

In accordance with another aspect of the invention there is provided an optical communications terminal, comprising: an optical telescope; a transmitter unit coupled to source of optical signals; a receiver unit for receiving optical signals; an optical system defining a transmit optical path between the optical telescope and the transmitter unit, and defining a receive optical path between the optical telescope and the transmitter unit; and characterised in that the transmitter unit comprises a plurality of transmitters, each transmitter being coupled to a respective source of optical signals.

In accordance with another aspect of the invention there is provided optical free space communications system, comprising: a first optical communications terminal, the first optical communications terminal being a terminal according to any of claims 1 to 30 of the appended claims; and a second optical communications terminal, the second optical communications terminal being a terminal according to any of claims 1 to 30 of the appended claims; wherein the first optical communications terminal and the second optical communications terminal are arranged whereby, in use, the transmitter unit of the first optical communications terminal may transmit said optical signals to the receiver unit of the second optical communications terminal and the transmitter unit of the second optical communications terminal may transmit said optical signals to the receiver unit of the first optical communications terminal.

An advantage of the present invention is that the same optical system that is used to send and receive high data rate optical signals is also used simultaneously by beacon optical signals for pointing, acquisition and tracking purposes.

Another advantage is that by disposing a greater proportion of the hardware in or near the focal plane, good optical alignment of the Tx and Rx beams can be attained and maintained.

A further advantage is that the use of multiple transmitters and multiple air paths enables a greater total power of signal to be employed. If several identical signal beams are sent, there is less susceptibility to error; and if several different signal beams are sent, the total data rate is higher.

Embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings. In the following, various embodiments are decribed, including a terminal adapted to be mounted on the ground (hereafter "ground demonstrator"). The drawings are briefly described as follows.

Fig. 1: schematic diagram of free space optical communication system.
Fig. 1.1: Ground Demonstrator Hardware Tree
Fig. 1.2. Schematics of the optical configuration.
Fig. 3.3. Transmission at 1550 nm: optical layout (only one of the 3 beams is shown).
Fig. 3.4. Beam shape (1550 nm) at the Rx telescope (only one of the 3 beams is shown).
Fig. 3.5. Reception at 1550 nm: optical layout (only one of the 3 beams is shown).
Fig. 3.6. Reception at 1550 nm: spot diagram (only one of the 3 beams is shown).
Fig. 3.7. Transmission of the beacon at 830 nm: optical layout.

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## 1. Introduction

Under an ESTEC Study there has been developed a low-cost lightweight terminal designed for Free Space Optics (FSO) communication, for example between collocated spacecrafts in geostationary orbit. Based on the use of the light-weight mirrors produced by Media Lario s.r.L. proprietary electroformed replication technology, the proposed terminal presents the following advantages:

- simple design with minimum number of components
- compact and light mass system, based on advantages of Nickel replicated mirrors
- large field of view in the focal plane of the telescope
- easy access to focal plane for tracking and communication purposes
- uniform power distribution inside the transmitted (Tx) beam; minimum losses
- high coupling in reception of Rx beam in Rx multi-mode fibre optics
- possibility to use gimbals systems for Pointing, Acquisition and Tracking without the necessity to include fast tracking devices
- symmetrical system to allow the link between any couple of terminals of a given constellation

The ground demonstrator described herein is based on the selected architectural design developed in the Study, where appropriate using commercial components with the purpose to demonstrate the function of the proposed architecture of the optical head at a low cost and therefore at a low risk. This is a necessary step in the development of a low cost light-weight ISL terminal.

The following description is of a ground demonstration terminal designed for communication at 2.5 Gbit/s between ground stations at a relative distance of 1.1 km. Only minor modifications, simplifications and improvements have been made compared to the terminal design proposed for the ISL scenario. The main change in the terminal configuration is relative to the use of "multi-beam transmission" (three Tx beams) for the compensation of atmospheric scintillation. Additionally, some optical bench components in the focal area of the telescopes have been adapted with the goal to use the Ritchey-Chrétien telescopes available from Media Lario; for this purpose three additional lenses have been added in order to extract the focus and make it accessible to accommodate the Rx fiber optics, the Tx fiber optics and the CCD camera. For the usage of the ground demonstrator under standard atmospheric environment and nominal operational conditions (ground application) with the same main technical solutions and concepts relative to the optical components and to the telecom equipment as for the Inter-Satellite link scenario, the tracking system has been simplified: it is constituted by simple manual positioners to guarantee correct pointing and tracking only for the short periods during the optical verifications.

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## 2. System Architecture

### 2.1 Overall Configuration

Referring to Fig. 1, two terminals, one transmitter and one receiver, consist each respectively of two subsystems, i.e. the Outdoor Unit (composed by the Optical Head and the Pedestal) and the Indoor Unit (the Transmitter Indoor Unit for the Transmitter Terminal and the Receiver Indoor Unit for the Receiver Terminal).

The Optical Head is identical both for the Transmitter Terminal and the Receiver Terminal; it comprises the Telescope, which is mounted on the Pedestal that provides manual gimbals movement for the alignment to the counter terminal. The Optical Bench includes all the components in the focal plane of the R-C telescope. The Optical Head is a compact assembly; it will be installed on an exposed site providing the necessary field of view with the remote terminal, without obscuration.

The Transmitter Indoor Unit and the Receiver Indoor Unit are connected respectively to the Transmitter and to the Receiver Optical Heads.

The Indoor Units includes all the electronics and the optoelectronics circuits and devices required to supply the required power, to convert the RF signals into the optical one and vice versa and to drive the lasers.

### 2.2 Functional Description

The Optical Head is the core of the free-space connection between two terminals. It is constituted mainly by a Ritchey-Chrétien telescope and by the opto-mechanical components to transmit and receive the optical signals from the Tx fiber optics to the Rx fiber optics.

The Transmitter Indoor Units and the Receiver Indoor Units supervise the operation of the Terminal and manages the control communication. The Indoor Units interface all the electronic sub-systems through a dedicated communication bus.

The main sub-systems of the Indoor Units are the Receiver Control Electronics and the Transmitter Control Electronics; they supervise the operation of Tx and Rx modules respectively by managing the required power, the enabling and the control signals and by monitoring their operational parameters in order to detect faults and failures. The transmitter control electronics also supervises the operation of the optical amplifier.

Pointing and acquisition are monitored by the CCD detector (in the Optical Head) and the electronics required for its operation (included in the Receiver Indoor Unit); its goal is the determination of the signal power and centroid co-ordinates of the signal collected by the CCD camera.

The pointing is performed through the gimbals manual mechanism of the Pedestal on which the optical head is mounted, based on the maintenance of the signal received by the CCD camera on a reference position set under laboratory conditions.

The acquisition is performed automatically once the pointing has been performed, being the transmitter and the receiver optical axis of the terminal set parallel under laboratory conditions.

Apart from the previously standard terminal functional operation, if needed the optical components can be moved from their positions so that typical experimental tests will be set with the goal to test the optical performance and the characteristics of the terminal, its stability and its degree of optimisation.

### 2.3 Interfaces


The Terminal possesses the following interfaces:

- Optical interface
- RF interface
- Power supply and grounding
- Mechanical mounting

A brief description of the various interfaces is provided below.

#### 2.3.1 Optical Interface

The optical design of the terminal has been performed assuming that no protective optical glass will be present in front of the terminal.

The optical constraint is that the lines of view (200 mm diameter for the 1550 nm radiation and 9 mm for the 830 nm beacon radiation, plus divergence) between the two connected terminals must be maintained free from mechanical obstructions.

### 2.3.2 RF Interface

The clock and data RF signals at both receiver and transmitter are connected to the indoor unit through standard SMA connectors. See Section 5 for more details.

### 2.3.3 Power Supply Interface

Each indoor unit can be supplied either at 230 $V_{AC}$ or 12 $V_{DC}$. The CCD camera is separately supplied at 12 $V_{DC}$ whereas the frame grabber is directly supplied by the PC. See Section 5 for more details.

### 2.3.4 Mechanical Interface

The optical head is mounted on the interface plate of the pedestal through 6 screws M6.

## 3. Optical Head

### 3.1 Overview on the Optical Head Configuration

The Optical Head configuration (the same for the Transmitter Terminal and for the Receiver Terminal) is shown and Fig. 1.2.

The following apply:

- One telescope is used as transmitter and receiver at the same time.
- In the focal plane of the telescope a series of optical components allow simultaneously to transmit and to receive optical signals at the identical wavelength of $\lambda = 1550$ nm at a data rate of 2.5 Gbit/s.
- One beacon at a wavelength of 830 nm is used for pointing and acquisition purposes. Its divergence is always maintained as large as 3.0 mrad. It is transmitted through a separate simple lens with useful optical diameter of 9 mm.
- In the focal plane of the R-C telescope the Rx signals at 830 nm and 1550 nm are separated by a beamsplitter and directed to the CCD and to the Rx multi-mode fiber optics respectively. An additional mirror with three small holes separates mechanically the Rx section (CCD and Rx multi-mode fiber optics 50/125 µm) from the Tx laser beams (full beam divergence = 190 µrad @ 1/e2 power angle; wavelength = 1550 nm; power of 1 mW out of each of the three Tx single-mode fiber optics) assuring optical isolation.
- The utilization of three transmitters reduces greatly the fluctuations of the intensity of the Rx beam caused by the turbulence of the atmosphere.
- Three achromatic doublets (diameter 25.4 mm) are used to extract the focus from the vertex of the primary mirror to the area in the back part of the telescope where the optical components can be accommodated.
- The optical components are mounted on translation and rotation stages to allow their correct fixation and alignment.

### 3.2 Optical Design

#### 3.2.1 Optical Design Overview

The optical design has been performed under the geometrical approximation.

#### 3.2.2 Beams size and shape

The size and shape of the beams (main channel at 1550 nm and beacon at 830 nm) have been evaluated along their path from the Tx fiber optics to the Rx section (the Rx fiber for the main channel at 1550 nm and the CCD camera for the beacon at 830 nm).

The calculations have been performed under the physical Gaussian approximation[1], and are shown in Table 3.1 below.

| Beam position | $\lambda = 1550$ nm Beam shape | $\lambda = 1550$ nm Beam size @ 13% ($1/e^2$) peak power | $\lambda = 830$ nm Beam shape | $\lambda = 830$ nm Beam size @ 13% ($1/e^2$) peak power |
|---|---|---|---|---|
| At the Tx fiber optics of the beacon | NA | NA | Gaussian | 5 µm |

[1] the data reported for the 1550 nm are relative to each of the three identical beams of the main channel.

| Beam position | λ = 1550 nm Beam shape | λ = 1550 nm Beam size @ 13% (1/e²) peak power | λ = 830 nm Beam shape | λ = 830 nm Beam size @ 13% (1/e²) peak power |
|---|---|---|---|---|
| At the Tx Beacon Simple Lens | NA | NA | Gaussian | 9 mm |
| At the Tx fiber optics of the main beam (1550 nm) | Gaussian | 10 μm | Gaussian | 5 μm |
| At the Tx collimation lens | Gaussian | 0.9 mm | NA | NA |
| At the Tx Hole mirror | Gaussian | 0.9 mm | NA | NA |
| At the Tx Relay lens | Gaussian | 0.9 mm | NA | NA |
| At the Tx telescope secondary mirror | Gaussian | 3 mm | NA | NA |
| At the Tx telescope primary mirror | Gaussian | 12 mm | NA | NA |
| At the Rx telescope | Gaussian (see Fig. 3.4) | 212 mm | Circular, uniform (see Fig. 3.8) | 3300 mm |
| At the Rx primary mirror | Elliptical | 125 mm x 190 mm | Circular, uniform | 200 mm |
| At the Rx secondary mirror | Elliptical | 30 mm x 48 mm | Circular, uniform | 50 mm |
| At the Rx Relay Lens | Elliptical | 9 mm x 14 mm | Circular, uniform | 15 mm |
| At the Rx Focusing lens for 830 nm | NA | NA | Circular, uniform | 15 mm |
| At the filter 830 nm | NA | NA | Circular, uniform | 8 mm |
| At the CCD | NA | NA | Circular, uniform (see Fig. 3.10) | 22 μm |
| At the Rx Focusing lens for 1550 nm | Elliptical | 9 mm x 14 mm | NA | NA |
| At the Rx fiber optics (at best position, i.e. 31.227mm from focusing lens, i.e. 200 μm in extrafocal position) | Circular, uniform (see Fig. 3.6) | 22 μm | NA | NA |
| | | | | |
| At the Rx fiber optics (at 31.127mm from focusing lens, i.e. 100 μm from focal position and 100 μm from. fiber | Circular, uniform | 45 μm | NA | NA |

| Beam position | $\lambda$ = 1550 nm Beam shape | $\lambda$ = 1550 nm Beam size @ 13% ($1/e^2$) peak power | $\lambda$ = 830 nm Beam shape | $\lambda$ = 830 nm Beam size @ 13% ($1/e^2$) peak power |
|---|---|---|---|---|
| optics position) | | | | |
| At the Rx fiber optics (at telescope focal position, i.e. 31.227mm from the focusing lens) | Circular, uniform | 70 µm | NA | NA |

Table 3.1. Beams shape and size.

### 3.2.3 Beams divergence

The divergence of the beams during the free-space propagation is reported in Table 3.2. For the 1550 nm beams it is determined by diffraction, while the divergence of the beacon is due to the positioning in intrafocal position of the transmitter fiber optics.

| | |
|---|---|
| **Divergence of the main beams at 1550 nm** | 190 µrad |
| **Divergence of the beacon at 830 nm** | 3.0 mrad |

Table 3.2. Beams divergence.

### 3.2.4 Fields of view & vignetting

The field of view of the Rx fiber optics has a size (diameter) of 100 mrad.

The field of view of the CCD camera is 13.0 x 8.6 mrad.

The optical components and their mechanical supports have been dimensioned so that no vignetting is present in a field of view of 8 mrad, both in the focal plane of the Rx fiber optics and in the focal palne of the CCD camera.

The system is expected however to operate only on axis: in fact any tip/tilt of the telescope will be compensated by the gimbals of the pedestal to maintain the coupling of the signal in the Rx fiber optics.

### 3.2.5Beams position (X, Y, Z)

The position (transversal X and Y with respect to the optical axis of the Ritchey-Chretien telescopes) of the centres of the beams has been evaluated along their path at the main planes, and reported in Table 3.3. The Z axis has been defined in the direction of the link; the Y axis is in the opposite versus (same direction) of gravity.
Table 3.4 shows instead the beam characteristics at the receiver fiber optics.

| Evaluation plane | $\lambda$ = 1550 nm Beam transversal position X with respect to optical axis | $\lambda$ = 1550 nm Beam transversal position Y with respect to optical axis | $\lambda$ = 830 nm Beam transversal position X w.r.t. optical axis | $\lambda$ = 830 nm Beam transversal position Y w.r.t. optical axis |
|---|---|---|---|---|
| At the Tx fiber optics of the beacon | NA | NA | +123.7 mm | +123.7 mm |
| At the Tx fiber optics of the main beam (1550 nm) | Beam 1: 0 mm<br>Beam 2: +5.187 mm | Beam 1: -5.99 mm<br>Beam 2: +2.995 mm | NA | NA |

| Evaluation plane | λ = 1550 nm Beam transversal position X with respect to optical axis | λ = 1550 nm Beam transversal position Y with respect to optical axis | λ = 830 nm Beam transversal position X w.r.t. optical axis | λ = 830 nm Beam transversal position Y w.r.t. optical axis |
|---|---|---|---|---|
| | Beam 3: -5.187 mm | Beam 3: +2.995 mm | | |
| At the Tx telescope primary mirror | Beam 1: 0 mm<br>Beam 2: -69 mm<br>Beam 3: +69 mm | Beam 1: +80 mm<br>Beam 2: -40 mm<br>Beam 3: -40 mm | NA | NA |
| At the Rx telescope | Beam 1: 0 mm<br>Beam 2: -69 mm<br>Beam 3: +69 mm | Beam 1: +80 mm<br>Beam 2: -40 mm<br>Beam 3: -40 mm | +123.7 mm | +123.7 mm |
| At the CCD (at best position, i.e. 18.2 mm from the focusing lens, i.e. 200 μm in extrafocal position) | NA | NA | +55.5 μm | +55.5 μm |
| At the Rx fiber optics (at best position, i.e. 31.227 mm from the focusing lens, i.e. 200 μm in extrafocal position) | Beam 1: 0 μm<br>Beam 2: -29 μm<br>Beam 3: -29 μm | Beam 1: +34 μm<br>Beam 2: -17 μm<br>Beam 3: -17 μm | NA | NA |
| At the Rx fiber optics (at 31.127 mm from the focusing lens, i.e. 100 μm from focal position and 100 μm from fiber optics position) | Beam 1: 0 μm<br>Beam 2: -22 μm<br>Beam 3: -22 μm | Beam 1: +26 μm<br>Beam 2: -13 μm<br>Beam 3: -13 μm | NA | NA |
| At the Rx fiber optics (at telescope focal position, i.e. 31.227mm from the focusing lens) | Beam 1: 0 μm<br>Beam 2: -16 μm<br>Beam 3: -16 μm | Beam 1: +19 μm<br>Beam 2: -10 μm<br>Beam 3: -10 μm | NA | NA |

Table 3.3: Beams position

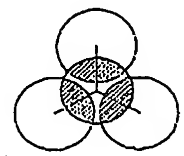
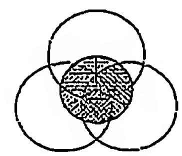
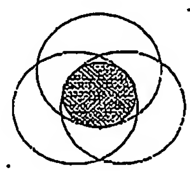
| Evaluation plane | Final Beam size | Schematics of the focal plane | Coupling efficiency into multi-mode fiber optics $\varnothing = 50\ \mu m$ |
|---|---|---|---|
| At the Rx fiber optics (at best position, i.e. 31.227 mm from the focusing lens, i.e. 200 µm in extrafocal position) | $[50^2_{manufacturing}+22^2_{optical\ design}]^{1/2}$ = 55 µm |  | 0.22 |
| At the Rx fiber optics (at 31.127 mm from the focusing lens, i.e. 100 µm from focal position and 100 µm from fiber optics position) | $[50^2_{manufacturing}+45^2_{optical\ design}]^{1/2}$ = 67 µm |  | 0.34 |
| At the Rx fiber optics (at telescope focal position, i.e. 31.227mm from focusing lens) | $[50^2_{manufacturing}+70^2_{optical\ design}]^{1/2}$ = 86 µm |  | 0.34 |

Table 3.4: Rx fiber optics reception plane.

### 3.3 Telescope Focal Plane

#### 3.3.1 The Optical Components

##### 3.3.1.1 <u>Position of the Optical Components</u>

The position of the optical component is presented in Fig. 1.3 here below.
The following should be noted:

- The focus of the 830 nm beacon is focalised shifted ($\Delta x$= +55µm; $\Delta y$=+55 µm) with respect to the centre of the CCD. His is due to the fact that the optical axis of the Tx beacon is shifted ($\Delta x$= +123.7mm; $\Delta y$=+123.7mm) with respect to the optical axis of the Tx Ritchey-Chrétien telescope.
- The fiber optics of the Tx beacon is 0.841 mm in intrafocal position to increase the divergence of the Tx beam; back focal length of the beacon lens is 46.641 mm at the reference wavelength of 830 nm.
- The focal plane where the Rx fiber optics is placed (18.0 mm from the filter) is the plane when a collimated beam is collected by the Rx telescope.
- The three arms of the spider do not intercept radiation of the three Tx beams which are placed at 60 deg with respect to the beams.

3.3.1.2 The R-C Telescope

The telescope is a Ritchey-Chrétien reflector (cf. Fig. 1.2 and Fig. 1.4) designed to have reduced dimensions, a large field of view and the possibility to accommodate the needed optical components in its focal plane.

The telescope optical and dimensional characteristics are reported here below:

- Optical configuration: Ritchey-Chrétien
- Primary mirror: Diameter = 200 mm (hole diameter = 20 mm)
  Radius of curvature = 315.8 mm concave
  Conic constant = 1.0667 (hyperbola)
- Secondary mirror: Diameter = 52 mm
  Radius of curvature = 110.8 mm convex
  Conic constant = -4.573 (hyperbola)
- Distance between mirrors = 120 mm
- Distance between secondary mirror and focal plane = 120 mm (without additional optical components in the focal plane)
- Effective focal length of the telescope = 500 mm
- Effective numerical aperture = 0.2
- Effective focal ratio = f/2.5
- Coating of primary and secondary mirrors = gold
- Reflectivity of the gold layer (at $\lambda$ = 1550 nm and $\lambda$ = 830 nm) – 98%

The telescope assembly is a compact unit, which can easily be handled without significant risks. In order to minimise the influence of the mechanical interface and environmental conditions, the telescope is mounted to the optical bench by means of three stainless steel blades distributed at a distance of 120° around the outer edge of the telescope. The blades are attached to the spider on one side. The blades are arranged such that the stiffness in tangential and longitudinal direction of the mirror is high while the stiffness in the radial direction is low, thus allowing for nearly unconstrained thermal expansion.

The telescope mechanical configuration is depicted in Fig. 1.5.

3.3.1.3 Relay Lens and the Focusing Lenses

The Relay Lens and Focusing Lenses are achromatic doublets introduced in the optical head to extract the focus of the Ritchey-Chrétien telescope from its inner position to an outer position to accommodate the components of the focal plane.
These lenses are identical. They have been designed for this specific purpose; additionally the beam emerging from the Relay Lens is collimated with advantages during its integration and for its propagation through the beamsplitter.

Availability: the Relay Lens and the Focusing Lenses are available from China Daheng Corporation (China). The technical characteristics of this specific product are the following:

- Type: cemented achromatic doublet
- Materials: LAKN22 and SFL6
- Diameter: 25.4 mm +0.0 / -0.2 mm
- Clear aperture: 23 mm
- Radii: 25mm, 18 mm, 81.66 mm
- Central thicknesses: 9 mm and 3 mm ± 0.1 mm
- Surface quality: 60-40
- Focal length: 48 mm ± 2%
- Surface figure: 1.5 $\lambda$ (vis)
- Coating: AR at 1650 nm
- Back focal length $_{@\lambda = 1550\,nm}$ = 31 mm

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### 3.3.1.4 The Hole Mirror

The Hole Mirror has the purpose to reflect the Rx radiation at 830 nm and 1550 nm respectively to the CCD and to the Rx multi-mode fiber optics, while the Tx radiation is transmitted through three holes of 3 mm in diameter of the mirror itself.

The amount of Rx power blocked by the holes is about 0.6 dB.

The Hole Mirror optical and dimensional characteristics are reported below:

- Coating: gold
- Diameter: 50 mm
- Number of holes: 3
- Holes diameter: 3 mm

Availability: the Hole Mirror is available from Gestione Silo S.r.l. (Italy).

### 3.3.1.5 The Beamsplitter 830/1550 nm

The Beamsplitter has a coating on the 45° facet so to reflect the 830 nm received signal to the CCD, and to transmit the 1550 nm signal to the Rx fiber optics.

The Beamsplitter optical and dimensional characteristics are reported below:

Availability: the Beamsplitter has been purchased from Optarius (UK). It has the following optical and dimensional characteristics:

- Part Number: 47-7437
- Longpass Filter
- 50% point: 900 nm
- Transmission at 1550 nm: > 80 %
- Reflection at 830 nm: > 80 %
- Angle of incidence of 45°
- Material: Borofloat Glass (BK7 in Zemax simulation)
- Diameter: 50 mm +0/-0.3 mm
- Thickness: 5 mm
- Flatness: λ/10 @ 632 nm
- Surface quality: 20-10

### 3.3.1.6 Tx Collimation Lens

The Tx Collimation Lens is a small lens placed just in front (3.644 mm) of each of the three Tx fiber optics to make the signal more converging (full beam divergence = 190 µrad @ $1/e^2$ power angle). In this way the Tx beams, whose divergence is due mainly to diffraction effects, have a very well corrected Gaussian profile. Advantages of this

configuration are that only small areas (Ø ≈ 12 mm each) of the Ritchey-Chrétien telescope are used by the Tx beams (the telescope has a Wave Front Error WFE < $\lambda/4$ P-V in any circular area with Ø = 20 mm) and the obscuration of the secondary mirror is avoided.

Availability: the Tx Collimation Lens is available from Edmund Scientific (USA). The technical characteristics of this specific product are the following:

- Code: A45-976
- Type: plano-convex lens
- Material: LaSFN30
- Diameter: 3 mm +0.0/-0.05 mm
- Clear aperture: 2.5 mm
- R1 (towards fiber optics): infinity
- Central thickness: 1.8 mm ± 0.1 mm
- R2: 3.62 mm
- Surface quality: 60-40
- Focal length: 4.5 mm ± 2%
- Centring Tolerance: 3-5 arcmin
- Bevel: 0.1 x 45°
- Coating: Telecom NIR (1250 nm – 1600 nm); reflection < 0.5 %

3.3.1.7 Rx MM fiber optics

The Rx MM fiber optics is a standard multi-mode fiber optics used for telecommunication.
Its optical and dimensional characteristics are reported here below:

- Corning® 50/125
- Type: multi-mode graded index
- Operating wavelength: 400 – 1800 nm (used at 1550 nm)
- $\varnothing_{core}$ = 50 µm ± 3 µm
- $\varnothing_{cladding}$ = 125 µm
- Numeric Aperture (N.A.) = 0.2 ± 0.015
- Connector: FC/PC

Availability: this fiber optics is manufactured by Corning (USA) and bought by ML at LIGHTECH (Italy)

3.3.1.8 Tx SM fiber optics for 1550 nm

The Tx SM fiber optics for the transmission of the 1550 nm signal is a standard single-mode fiber optics used for telecommunication.
Its optical and dimensional characteristics are reported here below:

- Corning® SMF-28™
- Type: single-mode

- Operating wavelength: 1260 - 1600 nm (used at 1550 nm)
- $\varnothing_{core} = 8.2\ \mu m$
- $\varnothing_{mode\ @\ \lambda = 1550\ nm} = 10.4\ \mu m \pm 0.8\ \mu m$ (well fitted with a Gaussian profile with $\varnothing_{beam\ waist} = 10\ \mu m$)
- $\varnothing_{cladding} = 125\ \mu m$
- N.A.@ $_{\lambda = 1550\ nm\ @\ 1/e^2\ power\ angle} = 0.094$
- Attenuation with bending diameter of 32 mm: < 0.5 dB
- Connector: FC/PC

Availability: this fiber optics is manufactured by CORNING (USA) and bought by LIGHTECH (Italy).

3.3.1.9 Tx Beacon Simple Lens

The beacon is transmitted through a simple objective lens placed outside the R-C terminal. The divergence of the beacon of 3.0 mrad (full beam divergence @ $1/e^2$ power angle) is obtained by positioning of the fiber optics through which the beacon is emitted in intrafocal position.

Availability: the Tx Beacon Simple Lens is available from Edmund Scientific (USA). The technical characteristics of this specific product are the following:

- Code: A45-486
- Type: plano-convex lens
- Material: BK7
- Diameter: 12 mm +0.0 / -0.1 mm
- Clear aperture: 11 mm (9 mm with mounting rings)
- R1 (towards fiber optics): infinity
- Central thickness: 2.5 mm ± 0.1 mm
- R2: 24.82 mm
- Surface quality: 60-40
- Focal length: 48 mm ± 2%
- Centring tolerance: 3-5 arcmin
- Bevel: 0.1 x 45°
- Coating: VIS-NIR (350 nm – 1050 nm); 0.5% reflection at 830 nm
- Back focal length $_{@\ \lambda = 632\ nm} = 46.194$ mm
- Back focal length $_{@\ \lambda = 830\ nm} = 46.641$ mm
- Fiber optics position for 3.0 mrad beam divergence $_{\lambda = 830\ nm\ @\ 1/e^2\ power\ angle} = 45.8$ mm from back lens surface.

3.3.1.10 Tx SM fiber optics for the beacon at 830 nm

The Tx fiber optics through which the beacon is emitted is a standard single-mode fiber optics used for telecommunication.

Its optical and dimensional characteristics are reported here below:

- 3M® FS-SN-4224
- Type: single-mode
- $\varnothing_{mode\ @\ \lambda = 830\ nm} = 5.6\ \mu m \pm 0.5\ \mu m$
- Operating wavelength: between 780 nm and 1020 nm (used at 830 nm)
- $\varnothing_{cladding} = 125\ \mu m$
- N.A.@ $_{\lambda = 830\ nm\ @\ 1/e^2\ power\ angle} = 0.094$
- Minimum bending mechanical diameter: 25 mm
- Connector: FC/PC

Availability: this fiber optics is manufactured by 3M (USA) and bought from LIGHTECH (Italy).

3.3.1.11 Filter 830 nm

The high sensitivity of the CCD camera (~ -95 dBm/px at 830 nm) requires avoiding as much as possible the presence of background radiation.

An IR band bass rejection filter has been therefore selected to be placed in front of the CCD.

Considering that:

- the stability of the wavelength of the selected 830 nm Tx laser is ±10 nm
- the typical tolerance of the central wavelength of this is type of filters is about ±10 nm
- the typical tolerance of the band pass (FWHM) of this is type of filters is about ±10 nm

the filter band pass has been selected with enough band width (FWHM = 50 nm) to cover the above tolerances, but not too large to avoid radiation from background.

Availability: the Filter 830 nm is available from Optarius (UK). It has the following optical and dimensional characteristics:

- Part Number: 47-7436
- Band pass Interference Filter
- Central wavelength: 830 nm ±8 nm
- FWHM: 50 nm ±10 nm
- Peak transmission: > 50 % @ 830 nm
- Angle of incidence; 90°
- Material: Soda Lime Glass (BK7 in ZEMAX® simulation)
- Blocking OD>4 from 200 nm to IR (reflectance > 99.9% @ 1550 nm)
- Diameter: 25 mm +0 / -0.25 mm
- Thickness: 3 mm
- Flatness: λ/10 @ 633 nm
- Surface quality: 20-10

3.3.1.12 Neutral Density Filter

The high sensitivity of the CCD camera (~ -95 dBm/px at 830 nm), the background radiation of the sky and the high intensity of the radiation of the beacon require the utilisation of a filter to reduce the intensity of the radiation collected by the CCD camera.

An neutral density filter (in addition to the band pass filter at 830 nm) has been therefore placed in front of the CCD.

Availability: the Neutral Density Filter is available from Newport (USA). It has the following optical and dimensional characteristics:

- Part Number: FSR-OD300
- Neutral Density Filter
- Surface flatness: < 1 λ at 632.8 nm over the clear aperture
- Diameter: 25.4 mm (clear aperture > 20.3 mm)
- Wedge: < 3 arcmin. Thickness: 2.5 mm

3.3.1.13 The CCD Camera

The selected CCD has been chosen being available as off-the-shelf equipment while being sensitive at 830 nm wavelength (after removal of the internal IR cut filter).

Availability: the CCD Camera has been purchased from Sony (USA).

Its main characteristics are reported here below:

- Model: XC-75CE (internal IR cut filter removed)
- Sensing area: 752 x 582 pixels = 6.5 x 4.3 mm (h x v)
- Pixel size: 8.6 x 8.3 µm (h x v)
- Weight: 140 g
- Lens mount: C-mount (Ø 25.4 mm; 32 tpi)
- Spectral response: 400-1000 nm
- Response at 830 nm with respect to peak response (at 500 nm): 15% (internal IR cut filter removed)
- Minimum illumination (internal IR cut filter removed): 0.5 lx (~ -95 dBm/px at 830 nm)

- Manual gain control: yes

### 3.3.2 The mechanical supports

#### 3.3.2.1 Supports for the Relay lens

The relay lens is mounted on:

- Translating lens mount for 1" optics, manufactured by Thorlabs Inc. (USA), code LM1XY/M, catalogue 2003, page 117, that allows translation adjustments of ±1 mm in x and y.
- Single axis steel translation stage, manufactured by Melles Griot (USA), code 07TES502 side drive, catalogue 2003, page 28.6, that allows translation of ±3 mm in z.

#### 3.3.2.2 Supports for the Hole Mirror

The Hole Mirror is mounted on:

- Lens mount for 2" optics, manufactured by Thorlabs Inc. (USA), code LMR2/M, catalogue 2003, page 97.
- Two single axis steel translation stages, manufactured by Melles Griot (USA), code 07 TES 502 side drive, catalogue 2003, page 28.6, that allows translation of ±3 mm in x and y.

#### 3.3.2.3 Supports for the Tx SM fiber optics for 1550 nm and for the collimation lens

Each of the three Collimation Lenses is mounted inside a cylindrical tube connected to the corresponding Tx fiber optics. These three systems are then inserted inside a larger tube that is mounted on:

- Gimbal mount for 1" optics, manufactured by Thorlabs Inc. (USA), code GM100/M, catalogue 2003, page 84, that allows tip/tilt with resolution of about 25 arcsec.

#### 3.3.2.4 Supports for the Beamsplitter 830/1550 nm

The Beamsplitter is mounted on:

- Lens mount for 2" optics, manufactured by Thorlabs Inc. (USA), code LMR2/M, catalogue 2003, page 97.

#### 3.3.2.5 Supports for the Focusing Lens of the CCD

The Focusing Lens of the CCD is mounted on:

- Translating lens mount for 1" optics, manufactured by Thorlabs Inc. (USA), code LM1XY/M, catalogue 2003, page 117, that allows translation adjustments of ±1 mm in x and y.

#### 3.3.2.6 Supports for the Focusing Lens of the Rx fiber optics

The Focusing Lens of the Rx fiber optics is mounted on:

- Translating lens mount for 1" optics, manufactured by Thorlabs Inc. (USA), code LM1XY/M, catalogue 2003, page 117, that allows translation adjustments of ±1 mm in x and y.

#### 3.3.2.7 Supports for the Filter at 830 nm and the Neutral Density Filter

The filters are mounted on a holder connected to the CCD camera.

#### 3.3.2.8 Supports for the CCD camera

The CCD camera is mounted on:

- Single axis steel translation stage, manufactured by Melles Griot (USA), code 07TES502 side drive, catalogue 2003, page 28.6, that allows translation of ±3 mm in z.

#### 3.3.2.9 Supports for the Rx fiber optics

The Rx fiber optics is mounted on:

- Fiber adapter, manufactured by Thorlabs (USA), code SM1FC, catalogue 2003, page 116.
- Translation stage, manufactured by Thorlabs (USA), code ST1XY-S/M, catalogue 2003, page 123, that allows translation of ±3.25 mm in x and y.
- Single axis steel translation stage, manufactured by Melles Griot (USA), code 07TES502 side drive, catalogue 2003, page 28.6, that allows translation of ±3 mm in z.

#### 3.3.2.10 Supports for the Tx Beacon Simple Lens

The Beacon Lens is mounted inside a cylindrical tube attached to the vertical plate of the optical head.

#### 3.3.2.11 Supports for the Tx SM fiber optics of the beacon at 830 nm

The Tx fiber optics of the beacon is mounted on:

- Fiber adapter, manufactured by Thorlabs (USA), code SM1FC, cat. 2003, page 116.
- Translation stage, manufactured by Thorlabs (USA), code ST1XY-S/M, catalogue 2003, page 123, that allows translation of ±3.25 mm in X and Y.
- Single axis steel translation stage, manufactured by Melles Griot (USA), code 07TES502 side drive, cat. 2003, page 28.6, that allows translation of ±3 mm in Z.
-

3.3.2.12 Supports for additional filters

Free space in front of the focusing lenses and in front of the Tx fiber optics has been left to insert, if needed, additional filters in case excessive radiation from external sources not considered in the current analysis will prevent the correct performance of the system.

## 4. Pedestal

The Pedestal is the support on which the Optical Head is mounted.

It is very stiff and heavy and provides therefore a stable support for the optical head.

The pedestals provide an azimuth and elevation manual adjustment capability so that the terminal can be aligned with respect to the counter terminal; the elevation and azimuth ranges are about ±200 mrad, quite large also to compensate possible mis-alignment during the initial installation of the terminals in the sites for the operational field tests.

The interface between the pedestal and the optical head is the horizontal aluminium plate of the Pedestal (with 6 holes Ø 8.5 mm) and the base plate of the Optical Head (with 6 holes M8).

## 5. Indoor Unit

The present section describes the design of the optoelectronic equipment required by the ISL ground demonstrator.

The design is based on off-the-shelf components as far as possible.

The hardware tree of the optoelectronic equipment is shown in Fig. 1.7. It mainly consists in three sections.

- The transmitter unit consists in two RF splitters that divide the input clock and data into two pairs of three identical signals that in turn are applied to three transmitter lasers. The unit also contains the beacon laser.
- The receiver unit contains the receiver that converts the input optical signal into the RF clock and data signals.
- The CCD camera and the frame grabber.

### 5.1 Transmitter Unit

The block diagram of the transmitter unit is shown in Fig. 1.8. The input clock and data RF signals are split by two passive devices in two pairs of three identical signals that in turn are applied to three transmitter lasers.

The transmitter unit also contains the beacon laser.

As an option an external off-the shelf optical amplifier can be used on one channel. In this case the other two channels are switched off. The optical amplifier is considered an instrument rather than part of the optoelectronic equipment.

#### 5.1.1 Radio Frequency Splitter

Two passive identical RF 1:4 splitters are used to split the clock and the data signals into four channels. One of the channels is not used and terminated by a 50 Ω impedance. A block diagram of each splitter is shown in **Error! Reference source not found.**.

The only main design challenge related to the splitter is the requirements to reduce to minimum the relative phase shift of the signals in the different splitter arms.

#### 5.1.2 Optical Transmitter

Each of the three optical transmitters is made by an off-the-shelf transmitter laser mounted, by soldering, on a custom board.

##### 5.1.2.1 <u>Transmitter Laser</u>

The technical specifications of the laser transmitter, Photon Technology PT9552-6-10-AA-FC, are listed in the Table 5.1 whereas its pin out is reported in Table 5.2. It is a complete 24 pins transmitter that converts the input RF clock and data signals into a modulated 1550 nm laser beam launched into a single mode fiber optics pigtail.

| Parameter | Conditions | Value | Unit |
|---|---|---|---|
| **Optical** | | | |
| Mean launched power | 50% duty cycle | 0 | dBm |
| Wavelength | - | 1500 – 1580 | nm |
| Line width | –20 dB | 0.5 | nm |
| Extinction ratio | - | 8.2 | dB |
| Optical rise and fall time | From 20% to 80% | 150 | ps |
| Fiber optics connector | - | FC | - |
| **Electrical** | | | |
| Bit rate | - | 50 – 2600 | Mb/s |
| RF clock and data voltage | Peak to peak | 0.2 – 1.6 | V |
| Input impedance | - | 50 | Ω |
| Supply voltage | Direct current | 5 | V |
| Power consumption | - | 1.5 | W |
| **Miscellaneous** | | | |
| Dimensions | - | 58.5x35.6x12.6 | $mm^3$ |
| Operating temperature | - | 0 – 65 | °C |

Table 5.1. Specifications of the Laser Transmitter, Photon Tech. PT9552-6-10-AA-FC.

| Pin # | Description | Pin # | Description |
|---|---|---|---|
| 1 | Not connected | 13 | Power supply |
| 2[1] | Back facet monitor | 14 | Not connected |
| 3[2] | Laser diode monitor | 15 | Ground |
| 4[3] | Laser diode shutdown | 16 | True data input |
| 5[4] | Clock mode select | 17 | Ground |
| 6 | Ground | 18 | False data input |
| 7 | Not connected | 19 | Ground |
| 8[5] | APC failure | 20 | True clock input |
| 9 | Not connected | 21 | Ground |
| 10 | Not connected | 22 | False clock input |
| 11 | Not connected | 23 | Ground |
| 12 | Not connected | 24 | Power supply |

Notes: 1) Voltage $V_2$ at pin #2 expresses photocurrent as $V_2$ mA.
2) Voltage $V_3$ at pin #3 expresses bias current as $50 \cdot V_3$ mA.
3) TTL input: diode laser is shutdown if input is high.
4) TTL input: retiming function is disabled if input is high.
5) TTL output: Automatic Power Control failed if output is high.

Table 5.2. Pin out of the Laser Transmitter, Photon Tech. PT9552-6-10-AA-FC.

5.1.2.2 <u>Transmitter Laser Board</u>

The transmitter board electric diagram is shown in Fig. 1.10. Two switches are foreseen on pins #5 and #6 whereas two output buffers on pins #2 and #3 allow the possible readout of the laser bias and laser current.

### 5.1.3 Beacon Laser Subassembly

The beacon laser subassembly is made by an off-the-shelf laser mounted on a off-the shelf driving board.

#### 5.1.3.1 Beacon Laser

The technical specifications of the beacon laser, PD-LD Inc. PL83 series (see Fig. 1.11), are listed in Table 5.3. The 3 pins device includes a photodiode for laser power control purposes and it is available with a single mode fiber optics pigtail.

| Parameter | Conditions | Value | Unit |
|---|---|---|---|
| Wavelength | - | 830 | nm |
| Wavelength stability | - | ± 10 | nm |
| Output power | - | 3 | mW |
| Operating current | - | 80 – 120 | mA |
| Photodiode monitor current | - | 40 – 130 | µm |
| Power consumption | - | ~0.3 | W |
| Fiber dimensions | - | 5/125 | µm |
| Fiber optics connector | - | FC | - |
| **Pin out** | | | |
| Pin #1 | Laser diode anode | | |
| Pin #2 | Common | | |
| Pin #3 | Photodiode Cathode | | |

Table 5.3. Specifications of the beacon laser, PD-LD Inc. PL83 series.

#### 5.1.3.2 Beacon Laser Driver

The driving of the beacon laser and the control of its output optical power is accomplished by an off-the-shelf driver, model CCA by Roithner Lasertechnik. The driver is available as a mounted printed circuit board and its main specifications are listed in Table 5.4.

| Parameter | Conditions | Value | Unit |
|---|---|---|---|
| Max. laser current | - | 120 | mA |
| Laser current adjustment | - | 0-120 | mA |
| Monitor current adjustment | - | 7.2 – 360 | µA |
| Supply voltage | Direct current | 2.7 – 6 | V |
| Power consumption | At 5 V | not available | W |
| Dimensions | - | 26×53 | $mm^2$ |

Table 5.4. Specifications of the beacon laser driver, Roithner Lasertechnik CCA.

#### 5.1.3.3 Integration of the Beacon Laser Subassembly

The beacon laser diode is integrated on the driver by direct soldering of its pins on the driver board.

A twin cable internal to the transmitter unit is soldered on the driver power supply pin-through-holes and connected to the 5 V power supply connector of the power supply unit (see Section 5.1.4).

### 5.1.4 Power Supply

The power supply accepts as input either 220 $V_{AC}$ or 12 $V_{DC}$. The output power supply is at 5 $V_{DC}$, 10 W.

### 5.1.5 Case and Harness

The receiver telecommunication equipment is housed in a standard case for a 19" rack, 1U. The transmitter case front and rear panel is shown in Fig. 1.12.

The transmitter indoor unit internal cable connections are shown in Fig. 1.13.

### 5.1.6 External Interfaces

A summary of the transmitter unit interfaces is listed in Table 5.5.

| Interface | Type | # | Description |
|---|---|---|---|
| **Optical** | | | |
| Transmitted data | Output | 4 | Single mode fiber, FC connector |
| Beacon | Output | 1 | Single mode fiber, FC connector |
| Spare | Output | 1 | Single mode fiber, FC connector |
| **Electrical** | | | |
| Clock | Input | 1 | Unbalanced, 50 Ω, SMA connector |
| Data | Input | 1 | Unbalanced, 50 Ω, SMA connector |
| Control | Output | 1 | D9 connector |
| Power supply | Input | 1 | 230 $V_{AC}$ or 12 $V_{DC}$ |
| **Mechanical** | | | |
| Case type | - | - | Rack 19", 1U |

Table 5.5. Transmitter unit interfaces.

## 5.2 Optical Amplifier

As an option an external off-the-shelf bench-top optical amplifier can be used on one of the output optical channels. In this case the other two channels are switched off.

The technical specifications of the optical EDFA, IPG Photonics EAD-1-C, are listed in Table 5.6.

| Parameter | Conditions | Value | Unit |
|---|---|---|---|
| Bandwidth | - | 1533 – 1567 | nm |
| Saturated power | - | 30 – 37 | dBm |
| Gain | - | 30 | dB |
| Noise figure | at 0 dBm input power | 5.5 | dB |
| Supply Voltage | Alternate current | 230 | V |
| Power consumption | - | 60 | W |
| Fiber connectors | - | FC | - |
| Operating temperature | - | 0 – 50 | °C |

Table 5.6. Specifications of the Optical Amplifier, IPG Photonics EAD-1-C.

Since the transmitter has a peak power of 3 dBm, the peak output of the amplifier is at 33 dBm equivalent to 2 W.

## 5.3 Receiver Unit

The block diagram of the receiver unit is shown in Fig. 1.14. The input optical signal is demodulated and the clock and data RF signals generated as output by the optical receiver. Refer to Section 5.1.3 for the beacon laser subassembly description.

### 5.3.1 Optical Receiver

The optical receiver is made by an off-the-shelf receiver mounted, by soldering, on a custom board.

5.3.1.1 Receiver

The technical specifications of the optical receiver, Photon Technology PT0236-6-FC, are listed in the Table 5.7 below. It is a complete receiver with data retiming and clock recovery, based on an InGaAs APD and supply with a 50 µm core multimode fiber optics.

| Parameter | Conditions | Value | Unit |
|---|---|---|---|
| **Optical** | | | |
| Wavelength | - | 1260 – 1650 | nm |
| Sensitivity (nominal) | 2.488 Gb/s, NRZ, BER = $10^{-9}$ | -28 | dBm |
| Overload | - | -8 | dBm |
| Fiber optics connector | - | FC | - |
| **Electrical** | | | |
| Bit rate | - | 2.488 | Gb/s |
| RF clock and data voltage | Peak to peak | 0.6 | V |
| Output impedance | - | 50 | Ω |
| Supply voltage | Direct current | 5 | V |
| Power consumption | - | not available | W |
| **Miscellaneous** | | | |
| Dimensions | - | 58.5×35.6×12.6 | $mm^3$ |
| Operating temperature | - | 0 – 65 | °C |

Table 5.7. Specification of the Receiver, Photon Tech. PT0236-6-FC.

| Pin # | Description | Pin # | Description |
|---|---|---|---|
| 1 | Not connected | 13 | Not connected |
| 2 | Not connected | 14 | Ground |
| 3[1] | Loss of power alarm | 15 | Ground |
| 4 | Ground | 16 | Ground |
| 5 | False clock input | 17 | Ground |
| 6 | True clock input | 18 | Not connected |
| 7 | Ground | 19 | Ground |
| 8 | Not connected | 20 | Ground |
| 9 | Ground | 21 | Not connected |
| 10 | True data input | 22 | Power supply |
| 11 | False data input | 23[2] | Optical input level |
| 12 | Ground | 24 | Not connected |

Notes: 1) TTL output: is high when average optical power is less than –35 dBm.
2) Voltage $V_{23}$ at pin #23 expresses average optical power as.

Table 5.8. Pin out of the Optical Receiver, Photon Tech. PT0236-6-FC.

5.3.1.2 Effect of Finite Extinction Ratio of the Optical Transmitter on the Receiver Sensitivity

The following approximate analysis has been performed to estimate the effect of the finite extinction ratio (8.2 dB) of the optical transmitter on the receiver sensitivity; an accurate analysis is not possible since a detailed description of the APD used in the detector is not available.

The analysis is based on the following assumption.

1) The receiver BER is equal to $10^{-9}$ at 2.5 Gbit/s, 50% duty cycle and –28 dBm average power, as stated in its specification. In addition it is assumed that this is valid for an infinite extinction ratio of the transmitter (i.e. when the transmitted power at zero logical level is zero).

2) The APD responsivity S is equal to 1 A/W, its gain factor M is equal to 10 and its noise factor F is equal to 7.57. The latter is a theoretical value derived from the relation **Error! Reference source not found.** F=kM + (1 – k)(2 – 1/M) with k=0.7 for InGaAs.

3) The receiver threshold is set to the midpoint between the optical power corresponding to logical one and zero.

At 50% duty cycle, the BER is given by **Error! Reference source not found.**

$$BER = \frac{1}{4}\left[\operatorname{erfc}\left(\frac{I_1 - I_{th}}{\sigma_1}\right) + \operatorname{erfc}\left(\frac{I_{th} - I_0}{\sigma_0}\right)\right]$$

where $I_1$ and $I_0$ are the detector current at logical one and zero respectively. $\sigma_1$ and $\sigma_0$ are the corresbonding noise. $I_{th}$ is the threshold current and erfc(x) is the complementary error function.

Setting $I_{th} = (I_1 + I_0)/2$ the BER becomes

$$BER = \frac{1}{4}\left[\operatorname{erfc}\left(\frac{I_1 - I_0}{2\sigma_1}\right) + \operatorname{erfc}\left(\frac{I_1 - I_0}{2\sigma_0}\right)\right]$$

As a first approximation the noise at the two logical levels differs by the contribution due to the signal shot noise in the bandwidth B=2.5 GHz. Thus $\sigma_1$ can be written as

$$\sigma_1 = \sqrt{\sigma_0^2 + 2qMF(I_1 - I_0)B}$$

Finally writing $I_0 = \eta I_1$, the BER reads

$$BER = \frac{1}{4}\left[\operatorname{erfc}\left(\frac{I_1(1-\eta)}{2\sqrt{\sigma_0^2 + 2qMFI_1(1-\eta)B}}\right) + \operatorname{erfc}\left(\frac{I_1(1-\eta)}{2\sigma_0}\right)\right] \qquad (1)$$

As discussed above, at infinite extinction ratio, i.e. at η=0, and at –28 dBm average power, the BER is at $10^{-9}$. Thus the equation

$$\frac{1}{4}\left[\operatorname{erfc}\left(\frac{I_1}{2\sqrt{\sigma_0^2 + 2qMFI_1}}\right) + \operatorname{erfc}\left(\frac{I_1}{2\sigma_0}\right)\right] = 10^{-9}$$

can be solved for $\sigma_0$. In the above equation $I_1 = P_1 MS$ where $P_1$ is the optical power of logic one, corresponding to –25 dBm. Solving the equation it is found that $\sigma_0$=3.352 μA.

Substituting this value back into relation (1) the BER can be plotted as a function of the extinction ratio, as shown in **Error! Reference source not found.**. It is seen that for an extinction ratio of 8.2 dB equal to the nominal value of the Photon Technology transmitter, the BER is $1.28 \cdot 10^{-7}$.

The following **Error! Reference source not found.** shows instead the BER as a function of the peak power $P_1$ for an extinction ratio of 8.2 dB. To recover a BER of $10^{-9}$ it is enough to increase the transmitted peak power by about 0.6 dB.

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#### 5.3.1.3 Receiver Board

The receiver board electric diagram is shown in Fig. 1.15. An output buffers on pin #23 allows the possible readout of the average input optical power.

### 5.3.2 Power Supply

The power supply accepts as input either 220 $V_{AC}$ or 12 $V_{DC}$. The output power supply is at 5 $V_{DC}$, 10 W.

### 5.3.3 Case and Harness

The receiver telecommunication equipment is housed in a standard case for a 19" rack, 1U. The receiver case front and rear panel is shown in **Error! Reference source not found.**.

The receiver indoor unit internal cable connections are shown in **Error! Reference source not found.**.

### 5.3.4 External Interfaces

A summary of the receiver unit interfaces is listed in Table 5.9.

| **Interface** | **Type** | **#** | **Description** |
|---|---|---|---|
| **Optical** | | | |
| Received data | Input | 1 | 50 µm core multi mode fiber, FC connector |
| Beacon | Output | 1 | Single mode fiber, FC connector |
| Spare | Output | 1 | Single mode fiber, FC connector |
| **Electrical** | | | |
| Clock | Output | 1 | Unbalanced, 50 Ω, SMA connector |
| Data | Output | 1 | Unbalanced, 50 Ω, SMA connector |
| Control | Output | 1 | D9 connector |
| Power supply | Input | 1 | 230 $V_{AC}$ or 12 $V_{DC}$ |
| **Mechanical** | | | |
| Case type | - | - | Rack 19", 1U |

Table 5.9. Transmitter unit interfaces.

## 5.4 CCD Camera and Frame Grabber

The CCD camera and the frame grabber are used for detection of the beacon signal. They have been both selected from off-the-shelf devices. Consequently no design activity is required and only brief description of them is given for completeness in the two next sections.

### 5.4.1 The CCD Camera

The technical specifications of the CCD camera, Sony XC-75CE, are listed in Table 5.10. The scanning is at 625 lines operated at both 2:1 interlaced and non-interlaced mode.

| **Parameter** | **Conditions** | **Value** | **Unit** |
|---|---|---|---|
| Optical size | - | 0.5 | inch |
| Effective picture elements | - | 752x582 | - |
| Total picture elements | - | 795x596 | - |
| Chip size | - | 7.95x6.45 | mm |
| Unit cell size | - | 8.6x8.3 | µm |
| Horizontal frequency | - | 15.625 | kHz |

| Parameter | Conditions | Value | Unit |
|---|---|---|---|
| Vertical frequency | - | 50 | Hz |
| Minimum illumination (without internal cut IR filter) | - | 0.5 | lux |
| Video output | Peak to peak | 1 | V |
| Output impedance | Unbalanced | 75 | Ω |
| Signal to noise ratio | - | 54 | dB |
| Supply voltage | Direct current | 12 | V |
| Power consumption | - | 1.4 | W |
| Operating temperature | - | –5 / +45 | °C |
| Weight | - | 140 | g |
| Dimensions | - | 71×44×29 | $mm^3$ |

Table 5.10. Specification of the CCD camera, Sony XC-75CE.

### 5.4.2 The Frame Grabber

The frame grabber is model IC-PCI-2.0 by Imaging Technology Inc. plus the AM-VS acquisition module by the same company. Few technical specifications are listed in Table 5.11.

| Parameter | Conditions | Value | Unit |
|---|---|---|---|
| Image Memory | - | 2 | MB |
| Interface | - | PCI bus | - |
| Image data access | - | 32 | bit |
| Control register access | - | 16 | bit |
| Acquisition frequency | 8 bit | 25 | MHz |
| Dimensions | - | 175×107 | mm |
| Power consumption | 5 V | 2.5 | W |
| Operating temperature | - | 10 – 60 | °C |

Table 5.11. Specifications of the frame grabber, Image Technology IC-PCI-2.0.

## 5.5 Functional Testing

The following Table 5.12 reports the list of the functional tests to be performed on the electronic equipment of the ground demonstrator.

| Test | Measured Parameter | Conditions | Acceptance |
|---|---|---|---|
| Beacon Laser stability | Power variations | 3 dBm | < 1 dB in 1 hour |
| Single channel communication | Sensitivity | BER = $10^{-9}$ | –28 dBm for 1 hour |
| Multi-channel communication | Sensitivity | BER = $10^{-9}$ | –28 dBm for 1 hour |

Table 5.12. Functional test list of the optoelectronic equipment.

The single channel communication tests will be done by connecting one transmitter laser at a time to the receiver by a 50 μm core multi mode fiber optics through an optical attenuator. The test will be done for all the transmitter lasers.

In the multi-channel communication test, the optical beams of all the transmitter lasers are added by means

of an optical coupler before being fed to the receiver.

# 6. Performance and Budgets

## 6.1 Dimensioning

The size of the terminal is as follows (as per **Error! Reference source not found.**):

- Outdoor Unit (Terminal): h = 660 x L = 451 mm x W = 422 mm
- Optical Head (cover included): h = 334 x L = 451 mm x W = 400 mm
- Pedestal: h = 300 x L = 353 mm x W = 397 mm
- Tx indoor unit: h = 132 x L = 483 mm x W = 270 mm
- Rx indoor unit: h = 132 x L = 483 mm x W = 270 mm

## 6.2 Mass Budget

The mass breakdown of the terminal is as follows:

- Outdoor Unit (Terminal): 62 kg
- Optical Head (cover included): 22 kg
- Pedestal: 40 kg
- Ritchey-Chrétien telescope: 1.3 kg
- Tx indoor unit: TBD
- Rx indoor unit: TBD

## 6.3 Eigenfrequencies

No structural analysis has been performed for the ground demonstrator in consideration that the goal of the present project is the demonstration of the optical and optoelectronical concepts developed during the feasibility study of the ISL terminal.

The structural analysis for the ISL terminal had been reported in **Error! Reference source not found.**.

## 6.4 Link Power Budget

A preliminary link power budget has been performed both for the main channel at 1550 nm and for the beacon at 830 nm; diffraction effects due to long distance propagation have been considered; however in this analysis the effects of disturbance of the atmosphere (power absorption, beam wandering, angle of arrival fluctuations) have not been considered and they will be analyses in details within phase 2 of the project.

Also power losses due to pointing and tracking errors have not been considered.

The results show that the link can be closed with additional power margin, as summarised in Table 6.1 here below:

| **Link power budget (link distance = 1114 m)** | **λ = 1550 nm (fiber optics core ∅ = 50 μm)** | **Beacon at λ = 830 nm (CCD Sony XC-75CE; pixels 8.6 μm x 8.3 μm)** |
|---|---|---|
| Transmit power (total output of the three fiber optics) | +4.8 dBm (→ 3 mW = 1 mW x 3) | +4.8 dBm (3 mW) |
| Connector loss in Tx | 0.3 dB | 0.3 dB |
| Optical bench loss in Tx | 0.1 dB<br>- Two surfaces of Collimation Lens: 0.05 dB<br>- Two surfaces of Relay Lens: 0.05 dB | Not applicable |
| Tx telescope loss | 0.2 dB<br>- Two gold coated mirrors: 0.2dB | 0.05 dB<br>- Two surfaces of Beacon Lens: 0.05 dB |
| Free space loss (including | 3.3 dB | 22.9 dB |

| Link power budget (link distance = 1114 m) | λ = 1550 nm (fiber optics core ∅ = 50 μm) | Beacon at λ = 830 nm (CCD Sony XC-75CE; pixels 8.6 μm x 8.3 μm) |
|---|---|---|
| entrance pupil – spider and secondary mirror – of Rx telescope) | - Divergence of 190 μrad: 1.6 dB<br>- Shift of Tx beam 80 mm with respect to optical axis: 1.7 dB | - Divergence of 3 mrad: 21.9 dB<br>- Shift of Tx beam 175 mm with respect to optical axis: 1.0 dB |
| Rx telescope loss | 0.2 dB<br>- Two gold coated mirrors: 0.2dB | 0.2 dB<br>- Two gold coated mirrors: 0.2 dB |
| Optical bench loss in Rx (comprising coupling with fiber optics) | 1.7 dB<br>- Two surfaces of Relay Lens: 0.05 dB<br>- 3mm holes of Hole Mirror: 0.5 dB<br>- Reflectivity of Hole mirror: 0.1dB<br>- Transmission loss of beamsplitter: 1.0 dB<br>- Two surfaces of Focusing Lens: 0.05 dB | <u>30.7</u> dB<br>- Two surfaces of Relay Lens: 0.05 dB<br>- 3mm holes of Hole Mirror: 0.5 dB<br>- Reflectivity of Hole mirror: 0.1dB<br>- Reflection loss of beamsplitter: 1.0 dB<br>- Two surfaces of Focusing Lens: 0.05 dB<br>- Filter at 830 nm: 3.0 dB<br>- <u>Neutral density filter: 26 dB</u> |
| Coupling with Rx fiber optics | 5.2 dB<br>- focus size of each beam (90% of energy in ∅ = 50 μm): 0.5 dB<br>- Superposition of 3 Rx beams: 4.7 dB | Not applicable |
| Coupling with CCD | Not applicable | 14.9 dB<br>- focus size (90% of energy in ∅ = 50 μm and pixel size 8.6μm x 8.3μm ): 14.9 dB |
| Connector loss in Rx | 0.3 dB | Not applicable |
| Power received by Rx fiber optics beginning of life | -6.5 dBm | Not applicable |
| Power received by one pixel of CCD begin of life | Not applicable. | <u>-64.2</u> dBm/px |
| Required power | >-28 dBm (<u>nominal value</u> for APD pigtailed detector of Photon Technology at 2.5 Gbit/s) | <u>≥-95</u> dBm/px (can be reduced through the manual gain control of the CCD) |
| Link margin | 21.5 dB | <u>30.8</u> dB |

Table 6.1: Link Power Budget.

### 6.4.1 Overview on background radiation

<u>Background radiation on the the CCD operating at 830 nm</u>

<u>Boundary conditions: - no direct solar illumination</u>
<u>- source of background radiation: solar illuminated sky (all sky excluding the Sun and some degrees around it)</u>
<u>- pixels size: 8.3 x 8.6 um</u>
<u>- 830 nm filter (FWHM = 50 nm) in front of CCD</u>

- neutral density filter (attenuation = 26 dBm) in front of CCD.

Maximum acceptable background on CCD: -95 dBm/pixel (see Section 3.3.1.13).

Calculation: taking into account that the Sun can be considered as a blackbody at temperature of 5800 K, it produces a flux ($W/m^2$) on Earth of:

$$F_{sole} = \frac{2hc}{\lambda^3} \frac{1}{e^{\frac{h\nu}{kT}} - 1} \frac{c\Delta\lambda}{\lambda^2} \left(\frac{R_s}{D_s}\right)^2$$

where:

- $h = 6.63 \cdot 10^{-34}$ J/°K
- $c = 3 \cdot 10^8$ m/s
- $\nu = 1.94 \cdot 10^{+14}$ $s^{-1}$
- $K = 1.38 \cdot 10^{-23}$ J·s
- T = 5800 K ; it is the sun temperature
- $D_s = 1.5 \cdot 10^{11}$ m; it is the distance of the Sun
- $2R_s = 7 \cdot 10^8$ m; it is the diameter of the Sun
- $\Delta\lambda$ is the part of the spectrum considered
- $\lambda$ is the central wavelength considered in the spectrum.

In our hypothesis, the central wavelength is $830 \cdot 10^{-9}$ m, and the part of the spectrum considered has a width of $50 \cdot 10^{-9}$ m due to the presence of the 830 nm filter with FWHM of 50 nm. In this case the flux on Earth is: 17.4 $W/m^2$.

If we take into consideration the size of the pixels and the additional attenuation of:

- 26 dB (neutral density filter);
- 14 dB (the CCD is not under direct solar illumination; this attenuation is an experimental result obtained in Media Lario on 8th April 2003 in a sunny day with clear sky conditions),

then the intensity of the background radiation on the CCD is -99 dBm/pixel, lower than the acceptable value of -95 dBm/pixel, and much lower than the peak intensity of the 830 nm signal (expected peak intensity: 64.2 dBm/pixel, as calculated in Section 6.4).

Conclusion: the selected Filter 830 nm (in addition to the Neutral Density Filter) assures enough isolation from solar background illumination.

Noise on the APD detector operating at 1550 nm

Boundary conditions: - no direct solar illumination
- source of background radiation: solar illuminated sky (all sky excluding the Sun and some degrees around it)
- 50/125 μm Rx fiber optics with numerical aperture 0.2

Maximum acceptable background in the Rx fiber optics: - 40 dBm (see **Error! Reference source not found.**)

Calculation: taking into account that:

- the radiation of the sun (entire spectrum) produces on Earth a flux of 1380 $W/m^2$;
- the diameter of the fiber optics is 50 μm;
- the fiber optics is not directly exposed to sun radiation but only to the solar illuminated sky (all sky excluding the Sun and some degrees around it); an experimental result obtained in Media Lario on 8th April 2003 has shown that the radiation collected by a fiber optics with numerical aperture of 0.2 in the mentioned conditions is 1/250 respect to a fiber optics under direct solar illumination.

then the amount of background radiation collected by the fiber optics is -50 dBm, lower than the acceptable value of -40 dBm.

Conclusion: the selected configuration (no band pass filter for 1550 nm radiation) assures enough isolation from solar background illumination.

### 6.4.2 Overview on polarization

The beams at 830 nm and 1550 nm are linearly polarised. For the foreseen test, no effect dependant on polarization effects has been identified. Therefore the utilisation of a quarter wave plate to transmit circular polarised radiation has not been implemented for the current demonstration on ground.

## 6.5 Power consumption

The power consumption of the terminals is reported in the following Table 6.2:

| Unit | Power Consumption |
|---|---|
| Tx indoor unit | < 10 W |
| Rx indoor unit | < 10 W |
| CCD camera | 2.5 W |
| Frame grabber of the CCD camera | 1.4 W |
| **Note: during the operations the following instrumentation will be used:** | |
| Optical Amplifier (Optional) | ~ 60 W |
| PC for Tx section | ~ 200 W |
| PC for Rx section | ~ 200 W |
| Pattern generator at 2.5 Gbit/s | < 300 W |
| BER detector | < 300 W |

Table 6.2: Power consumption.

## 7. Conclusions

The design of the optical head ground demonstrator is representative of the ISL terminal architecture. In order to minimize the efforts and to account for the test boundary conditions under the atmospheric disturbances, the following changes and additional features have been implemented:

- A total number of 3 transmit beams is used to reduce the effects of the scintillation of the atmosphere
- Relay lenses have been introduced in order to allow the utilization of the existing telescope design
- Commercial off-the-shelf components are used for the electrical and electronics devices. Their suitability for space application is not checked.
- A simple manual pointing and tracking system has been included to perform the optical communication tests at 2.5 Gbit/s

These changes do not fundamentally modify the architecture and the functionality of the terminal. They will only improve the availability of the link under ground environmental conditions. The influence of the deviation of the design and of the environmental conditions will be considered during test predictions.

The design of the demonstrator is completed; upon review by ESA, procurement and manufacturing phases[2] can be initiated.

[2] Please note that anyway, as outlined in the specific locations along this report, the procurement of some standard long-lead items, already thoroughly discussed, was already started.

ANNEX 1

| List of Acronyms | | | |
|---|---|---|---|
| AC | Alternate Current | MM | Multi Mode |
| AD | Applicable Document | N.A. | Numeric Aperture |
| APD | Avalanche Photo Diode | NA | Not Applicable |
| AR | Anti Reflection | NRZ | Non Return to Zero |
| BER | Bit Error Rate | OH | Optical Head |
| cf. | see | OR | Original |
| CCD | Charge Coupled Device | PC | Personal Computer |
| DC | Direct Current | P-V | Peak to Valley |
| e.g. | exempli gratia (for example) | R-C | Ritchey-Chrétien |
| EDFA | Erbium Doped Fiber Amplifier | RD | Reference Document |
| ESA | European Space Agency | RF | Radio Frequency |
| ESTEC | (ESA) European Space Research and Technology Centre | Rx | Receiver |
| FO | Fiber Optics | SM | Single Mode |
| FSO | Free Space Optics | TBD (tbd) | To be defined |
| FWHM | Full Width Half Maximum | Tx | Transmitter |
| H/W | Hardware | TTL | Transistor-Transistor Logic |
| i.e. | id est (that is) | vs. | versus |
| IL | (ML) Optical Telescope for ISL Feasibility Study Project | WFE | Wavefront Error |
| IR | Infra Red | w.r.t. | with respect to |
| ISL | Inter-satellite Link | ZEMAX® | Focus Software Inc. Optical Analysis Package |
| ML | Media Lario S.r.l. | | |

**Claims:**

1. An optical communications terminal, comprising:
an optical telescope;
a transmitter unit including at least one transmitter coupled to source of optical signals;
a receiver unit for receiving optical signals;
an optical system defining a transmit optical path between the optical telescope and the transmitter unit, and defining a receive optical path between the optical telescope and the receiver unit; and
a beacon detector for detecting beacon optical signals received at the optical telescope;
characterised in that a beacon optical path between the optical telescope and the beacon detector comprises at least a portion of said transmit optical path and/or said receive optical path.

2. The terminal of claim 1, wherein the transmitter unit, receiver unit and beacon detector are disposed at or adjacent the focal plane of the optical telescope.

3. The terminal of claim 1 or 2, wherein the optical system includes a relay lens and a first mirror, and the optical path between said first mirror and the optical telescope is common to the transmit optical path, the receive optical path and the beacon optical path.

4. The terminal of claim 3, wherein the optical system includes a beamsplitter between the first mirror and the receiver unit, the beamsplitter, in use, passing receiver optical signals along the transmit optical path to the receiver unit and reflecting beacon optical signals along the beacon optical path to the beacon.

5. The terminal of any of the preceding claims, wherein the transmitter unit includes a plurality of transmitters.

6. The terminal of any of the preceding claims, wherein for the or each transmitter an aperture is provided in the first mirror, a separate transmit optical path thereby being provided from the or each transmitter to the optical telescope via a respective aperture.

7. The terminal of any of the preceding claims, wherein the or each transmitter comprises the terminating portion of a single mode optical fibre, a collimating lens preferably being provided at said terminating portion in a respective transmit optical path.

8. The terminal of claim 5, and any claim dependent thereon, wherein each transmitter is fed by the same optical signal.

9. The terminal of claim 5, and any claim dependent thereon, wherein each transmitter is fed by a different optical signal.

10. The terminal of claim 5, and any claim dependent thereon, wherein there are three transmitters.

11. The terminal of any of claims 4 to 10, wherein the beacon optical path includes a second focussing lens between said beamsplitter and the beacon detector.

12. The terminal of claim 11, wherein the beacon optical path includes a filter system between said second focussing lens and the beam detector, the filter system preferably including, in sequence, a filter passing a first predetermined frequency and a neutral density filter.

13. The terminal of claim 11, wherein the first predetermined frequency is 830nm.

14. The terminal of any of the preceding claims, wherein the receiver unit includes one receiver for receiving optical signals at a second predetermined frequency, different to said first predetermined frequency, said second predetermined frequency preferably being 1550 nm.

15. The terminal of claim 14, wherein the receiver comprises a terminating portion of a multimode optical fibre.

16. An optical communications terminal, comprising:
an optical telescope;
a transmitter unit coupled to source of optical signals;
a receiver unit for receiving optical signals;

an optical system defining a transmit optical path between the optical telescope and the transmitter unit, and defining a receive optical path between the optical telescope and the transmitter unit; and

characterised in that the transmitter unit comprises a plurality of transmitters, each transmitter being coupled to a respective source of optical signals.

17. The terminal of claim 16, wherein for the or each transmitter an aperture is provided in the first mirror, a separate transmit optical path thereby being provided from the or each transmitter to the optical telescope via a respective aperture.

18. The terminal of claim 16 or 17, wherein the or each transmitter comprises the terminating portion of a single mode optical fibre, a collimating lens preferably being provided at said terminating portion in a respective transmit optical path.

19. The terminal of any of claims 16 to 18, and any claim dependent thereon, wherein each transmitter is fed by the same optical signal.

20. The terminal of any of claims 16 to 19, and any claim dependent thereon, wherein each transmitter is fed by a different optical signal.

21. The terminal of any of claims 16 to 20, and any claim dependent thereon, wherein there are three transmitters.

22. The terminal of any of claims 16 to 21, further including a beacon detector for detecting beacon optical signals received at the optical telescope.

23. The terminal of claim 22, wherein the transmitter unit, receiver unit and beacon detector are disposed at or adjacent the focal plane of the optical telescope.

24. The terminal of claim 22 or 23, wherein the optical system includes a relay lens and a first mirror, and the optical path between said first mirror and the optical telescope is common to the transmit optical path, the receive optical path and the beacon optical path.

25. The terminal of claim 24, wherein the optical system includes a beamsplitter between the first mirror and the receiver unit, the beamsplitter, in use, passing receiver optical signals along the transmit optical path to the receiver unit and reflecting beacon optical signals along the beacon optical path to the beacon.

26. The terminal of any of claims 22 to 25, wherein the beacon optical path includes a second focussing lens between said beamsplitter and the beacon detector.

27. The terminal of any of claims 22 to 26, wherein the beacon optical path includes a filter system between said second focussing lens and the beam detector, the filter system preferably including, in sequence, a filter passing a first predetermined frequency and a neutral density filter.

28. The terminal of any of claims 22 to 27, wherein the first predetermined frequency is 830nm.

29. The terminal of any of claims 22 to 28, wherein the receiver unit includes one receiver for receiving optical signals at a second predetermined frequency, different to said first predetermined frequency, said second predetermined frequency preferably being 1550 nm.

30. The terminal of claim 29, wherein the receiver comprises a terminating portion of a multimode optical fibre.

31. An optical free space communications system, comprising:

a first optical communications terminal, the first optical communications terminal being a terminal according to any of the preceding claims; and

a second optical communications terminal, the second optical communications terminal being a terminal according to any of the preceding claims;

wherein the first optical communications terminal and the second optical communications terminal are arranged whereby, in use, the transmitter unit of the first optical communications terminal may transmit said optical signals to the receiver unit of the second optical communications terminal and the transmitter unit of the second optical communications terminal may transmit said optical signals to the receiver unit of the first optical communications terminal.

Abstract

**Free space optical communications**

An optical communications terminal, comprising: an optical telescope (e.g. a dual mirror Ritchie-Chretien telescope); a transmitter unit including at least one transmitter coupled to source of optical signals; a receiver unit for receiving optical signals; an optical system defining a transmit optical path between the optical telescope and the transmitter unit, and defining a receive optical path between the optical telescope and the receiver unit; and a beacon detector for detecting beacon optical signals received at the optical telescope; characterised in that a beacon optical path between the optical telescope and the beacon detector comprises at least a portion of said transmit optical path and/or said receive optical path. In one embodiment, the transmitter unit, receiver unit and beacon detector are disposed at or adjacent the focal plane of the optical telescope, providing a compact arrangement suitable for usage in diverse environments (e.g. aircraft- or satellite-borne, as well as ground-based). In another aspect of the invention there is disclosed an optical communications terminal in which the transmitter unit comprises a plurality of transmitters, each transmitter being coupled to a respective source of optical signals. An optical free space communications system comprising two such coupled terminals is also disclosed.

*(Fig. 1 )*

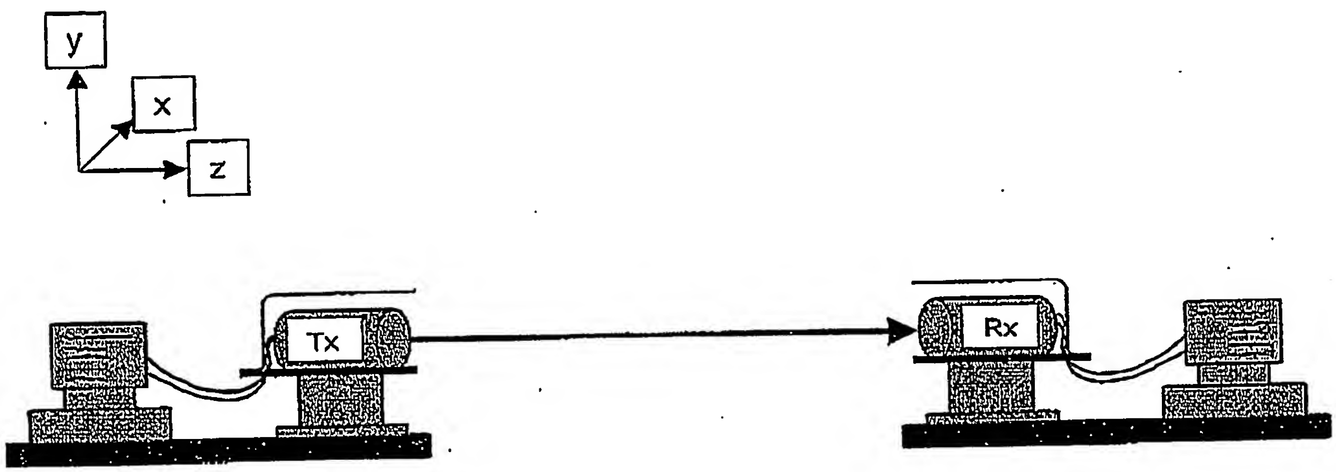



Fig. 1

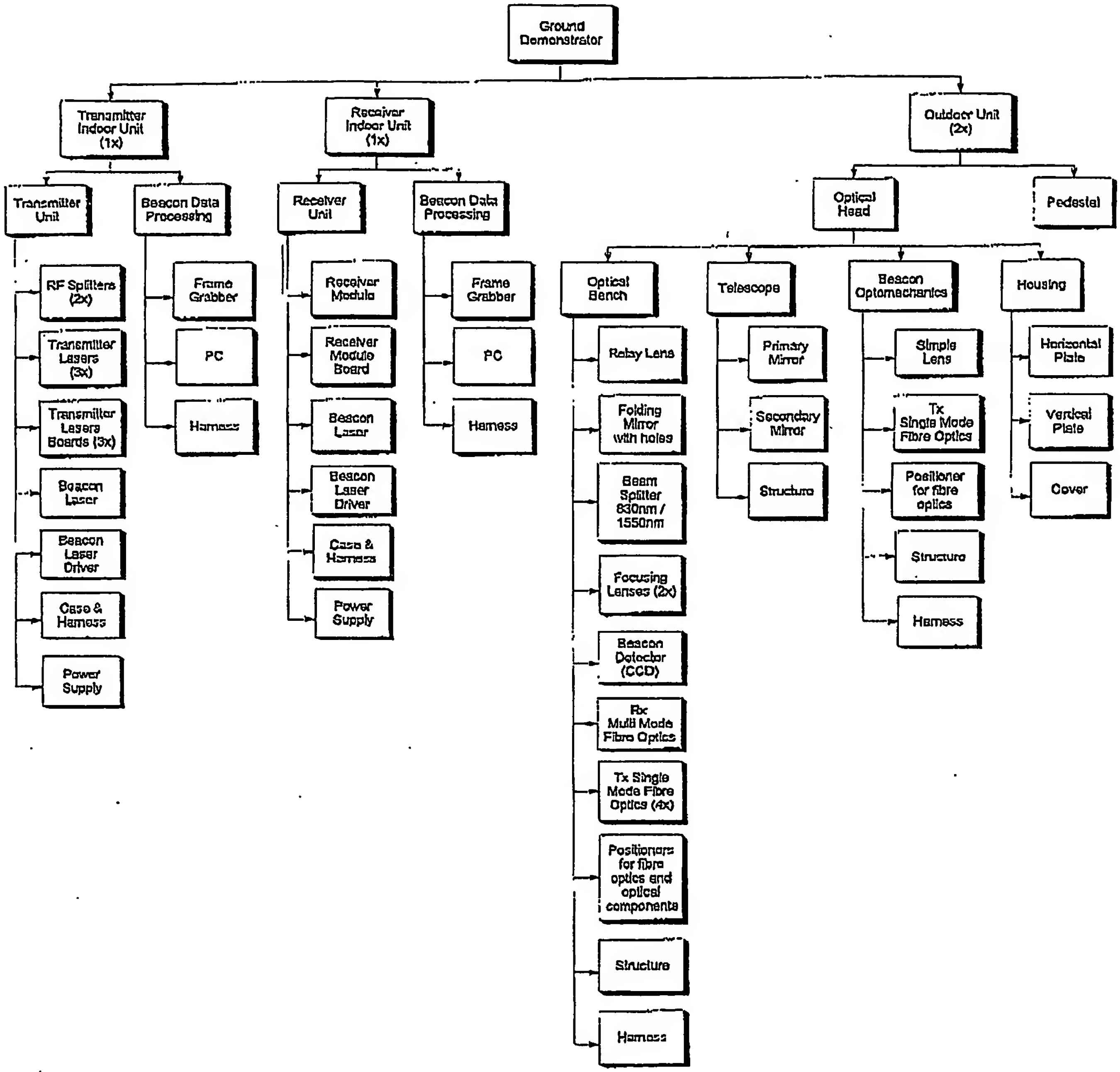



*Fig. 2.2: Ground Demonstrator Hardware Tree*

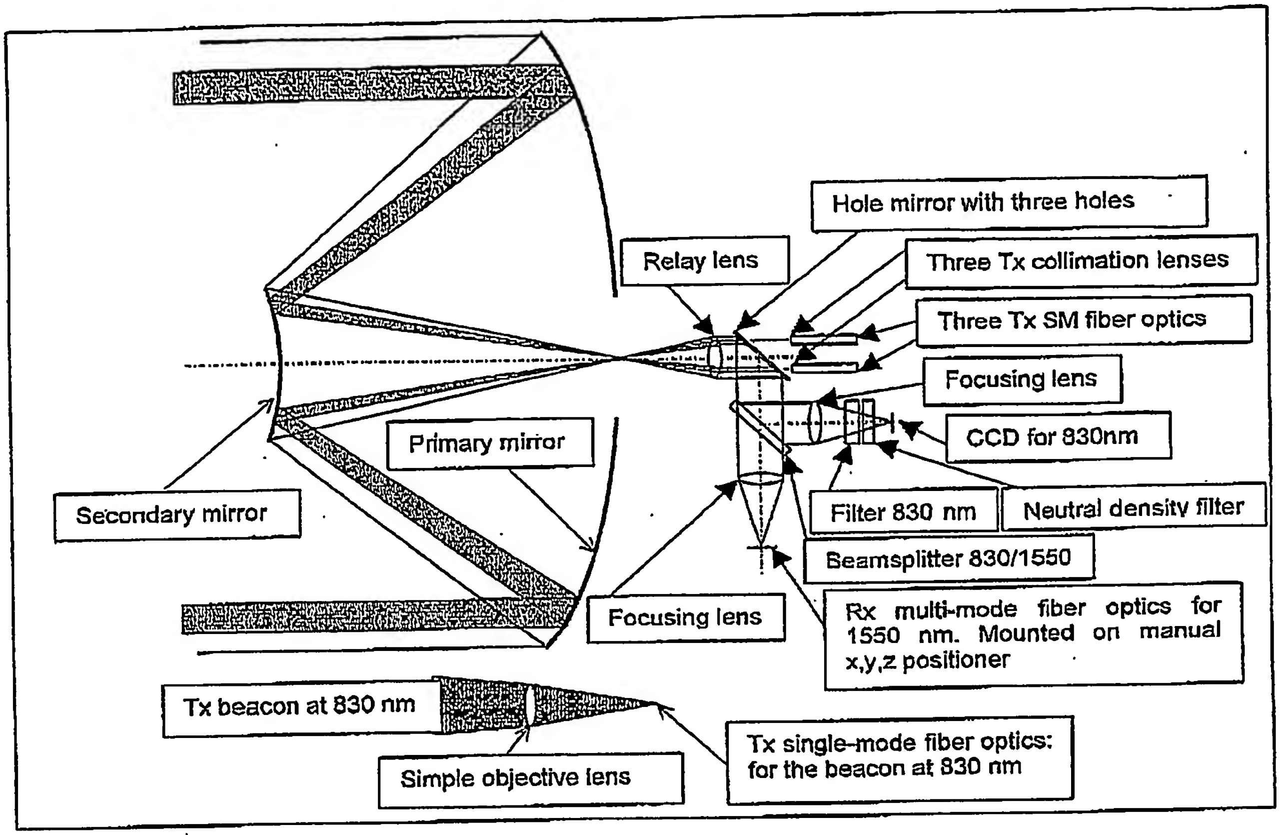



*Fig. 3.2. Schematics of the optical configuration.*

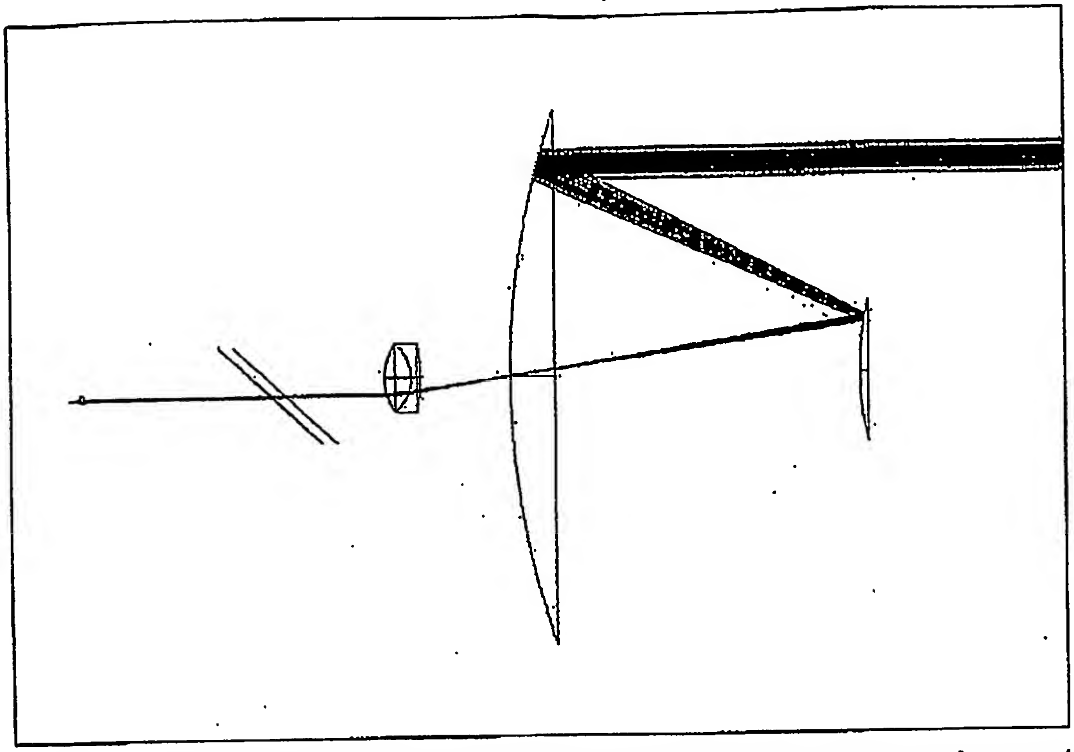


Fig. 3.3. Transmission at 1550 nm: optical layout (only one of the 3 beams is shown).

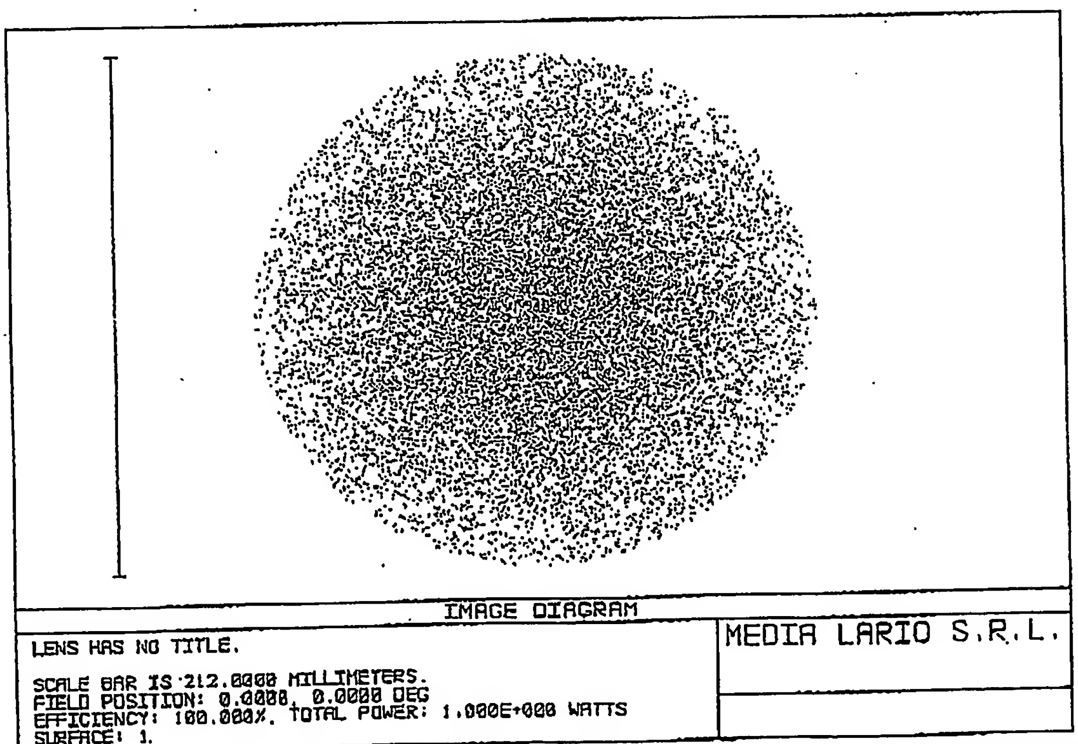



Fig. 3.4. Beam shape (1550 nm) at the Rx telescope (only one of the 3 beams is shown).

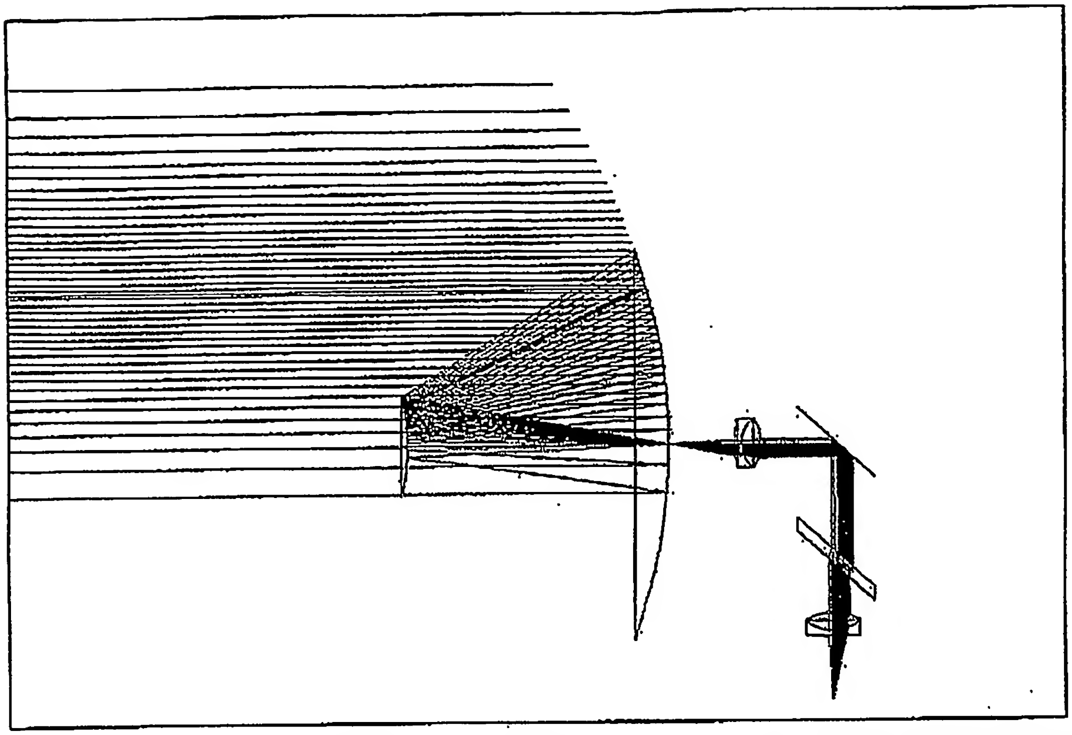


Fig. 3.5. Reception at 1550 nm: optical layout (only one of the 3 beams is shown).

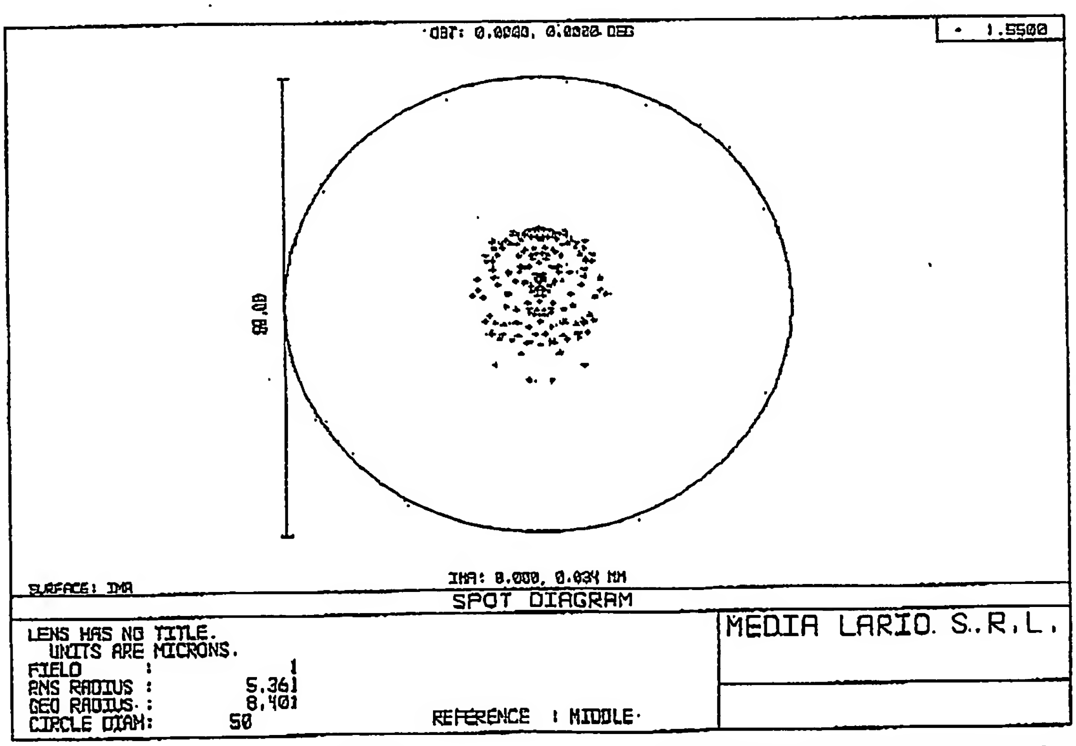



Fig. 3.6. Reception at 1550 nm: spot diagram (only one of the 3 beams is shown).

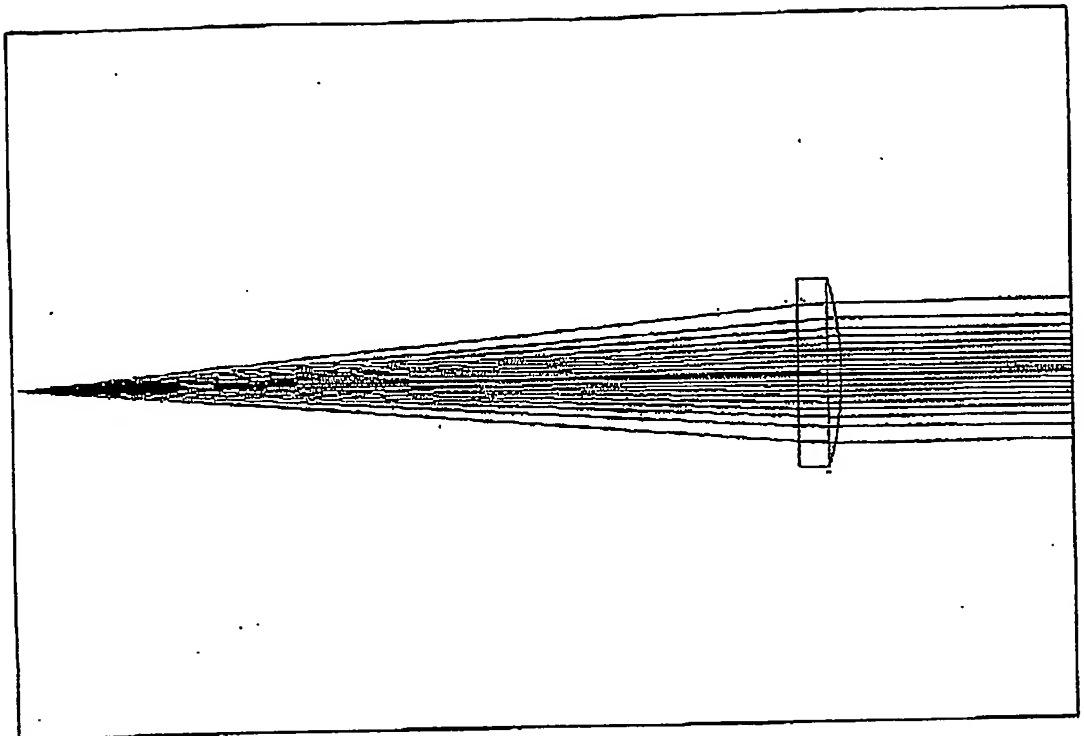


Fig. 3.7. Transmission of the beacon at 830 nm: optical layout.

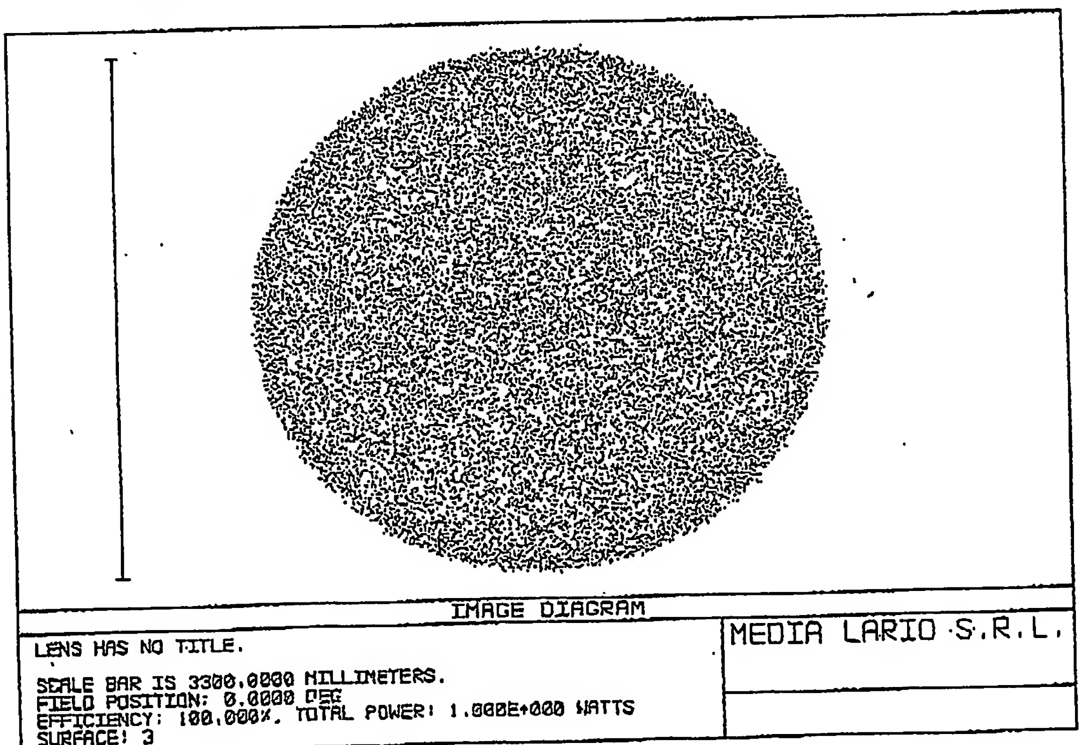



Fig. 3.8. Beam shape (beacon at 830 nm) at the Rx telescope.

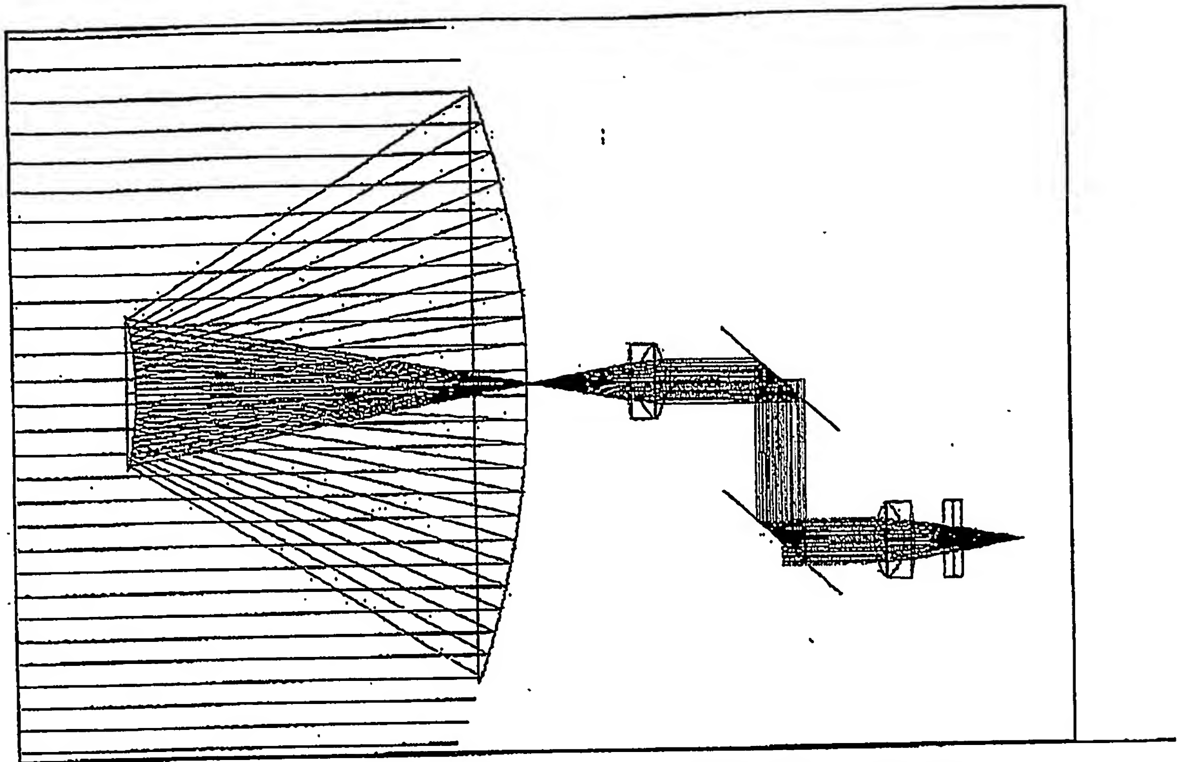


Fig. 3.9. Reception of the beacon at 830 nm: optical layout.

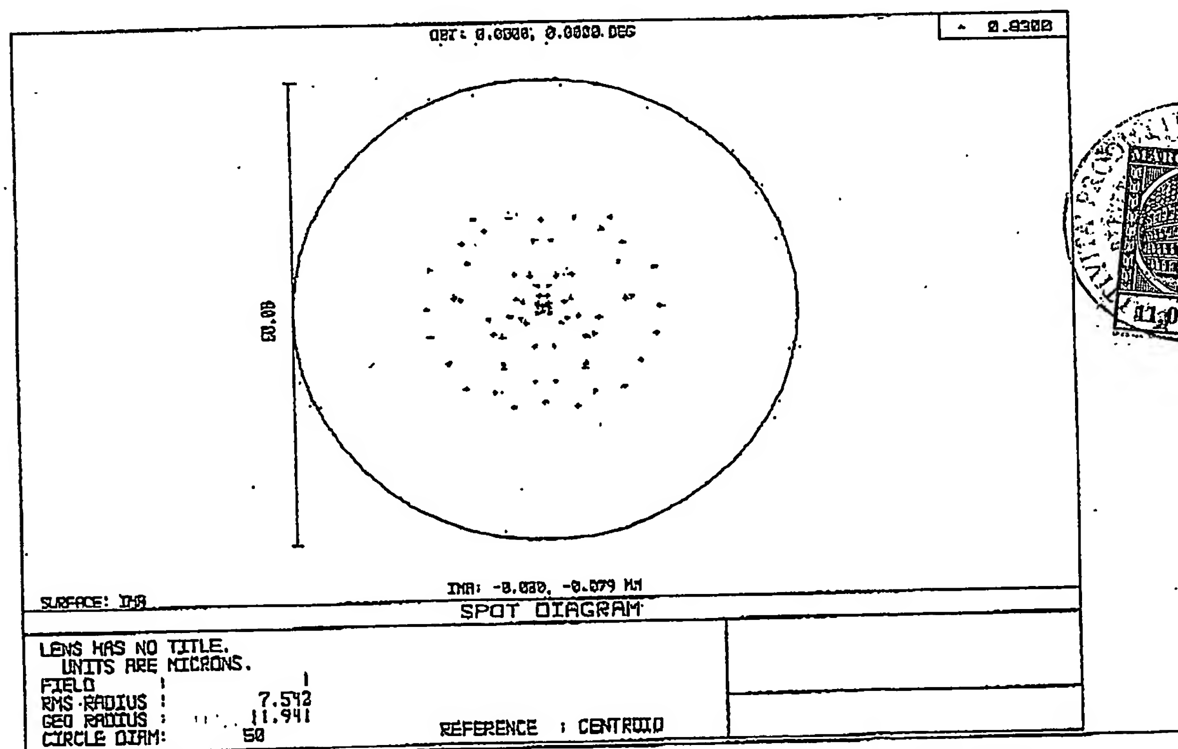



Fig. 3.10. Reception of the beacon at 830 nm: spot diagram

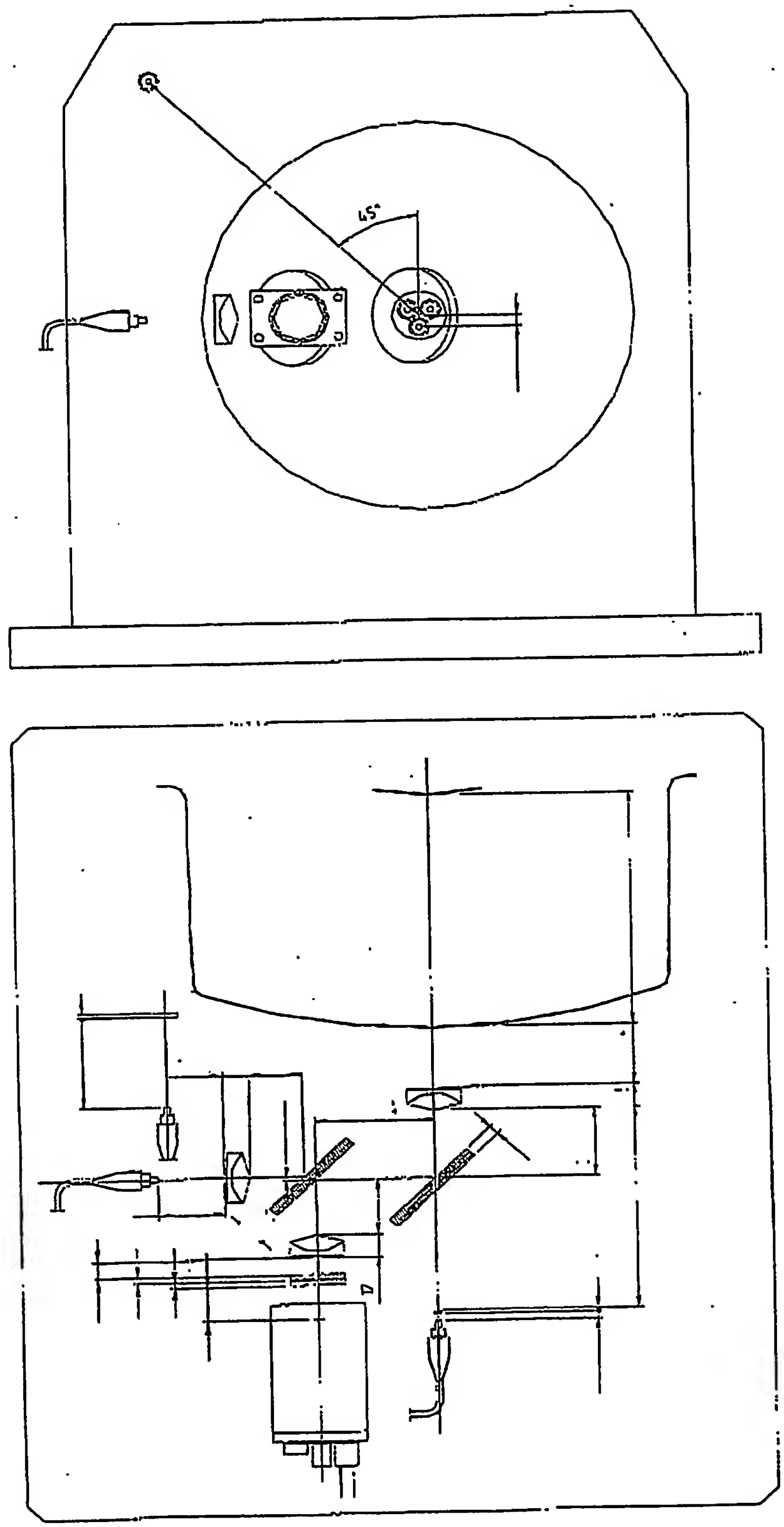



Fig.3.11 Positions of the optical components (only one Tx is shown)

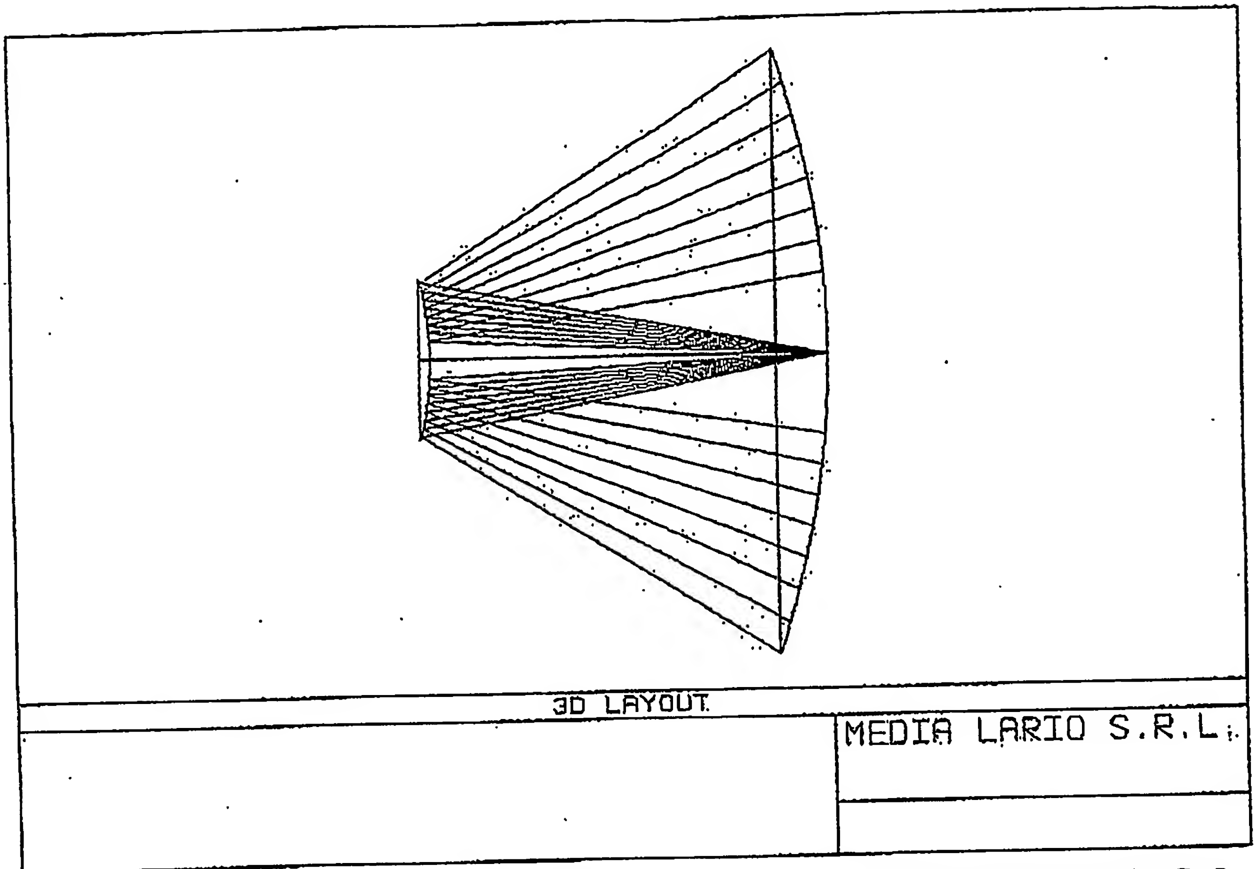



Fig. 3.12 Optical layout of the R-C telescope.

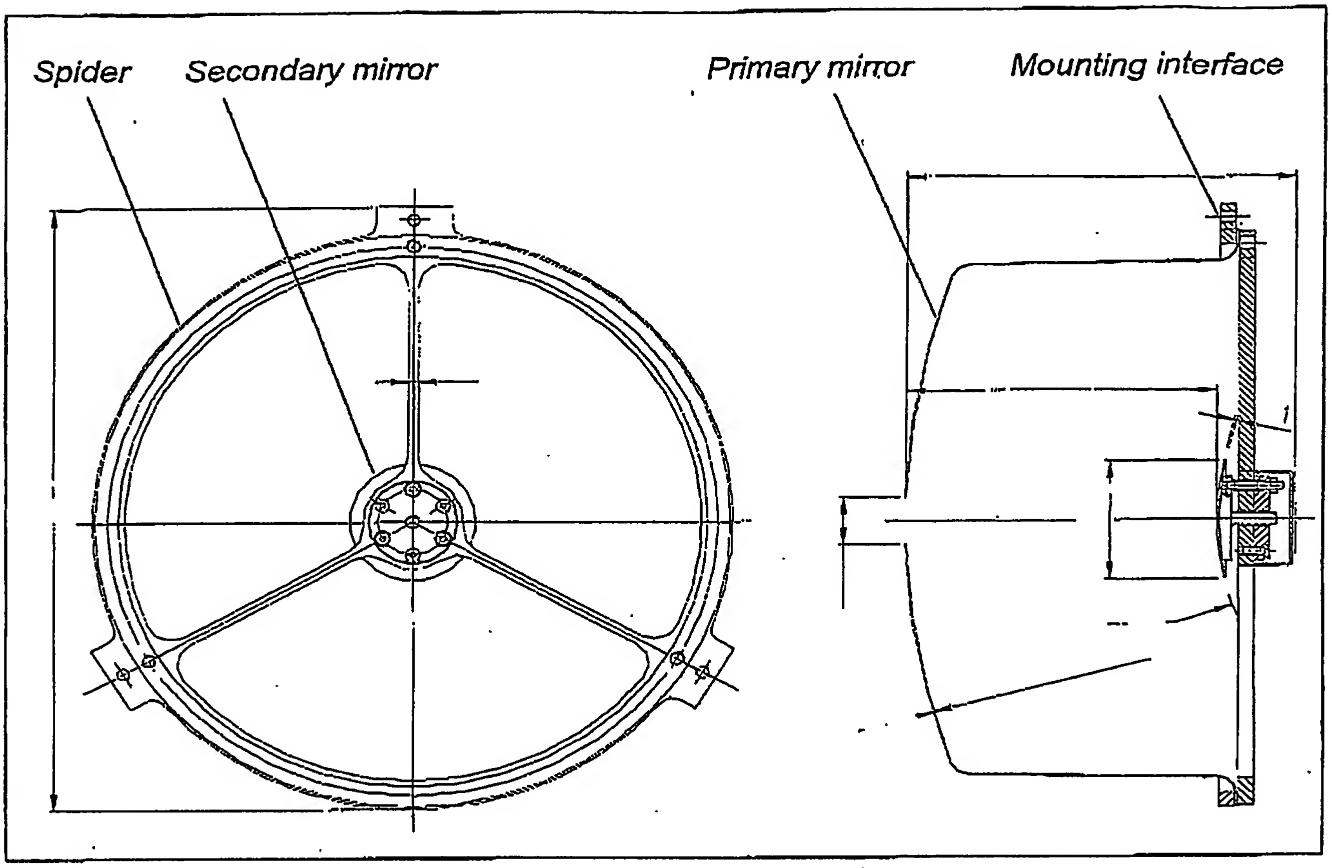



Fig.3.13 Telescope Assembly

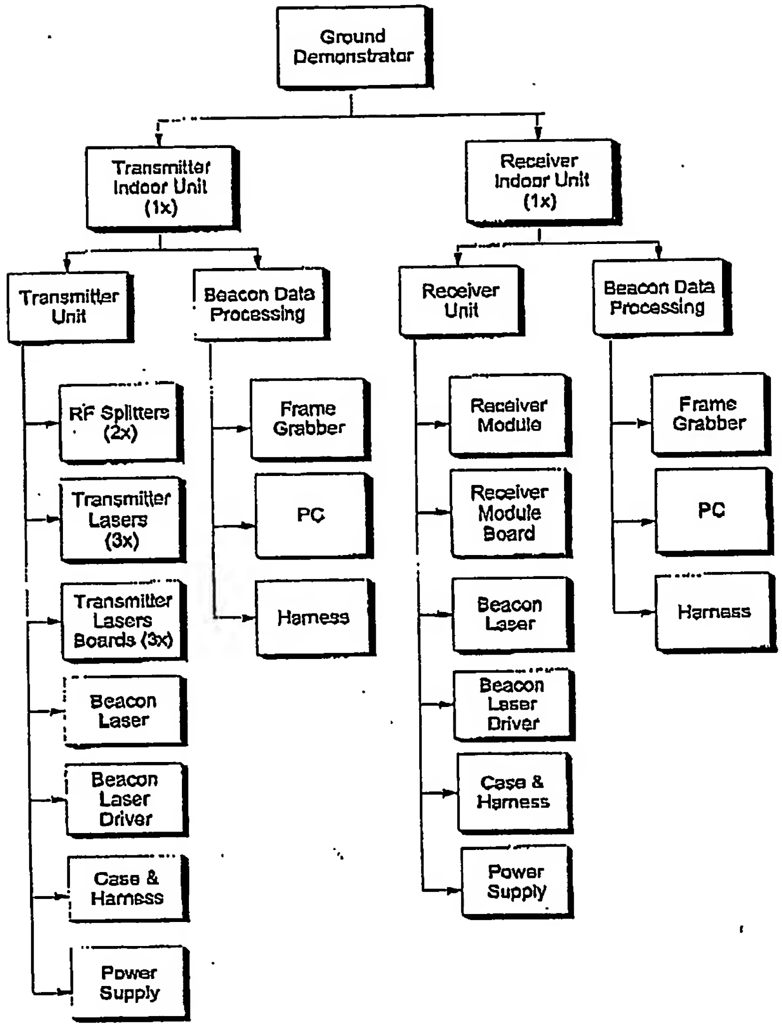



*Fig. 5.1: Indoor Units Hardware Tree.*

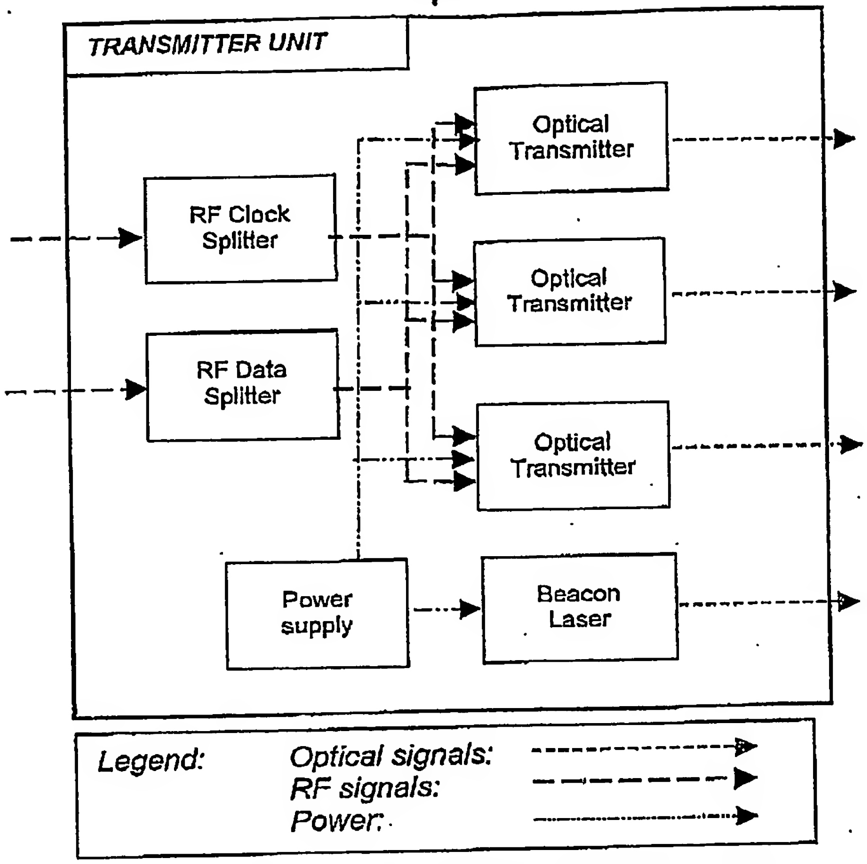



Fig. 5.2: Transmitter functional block diagram.

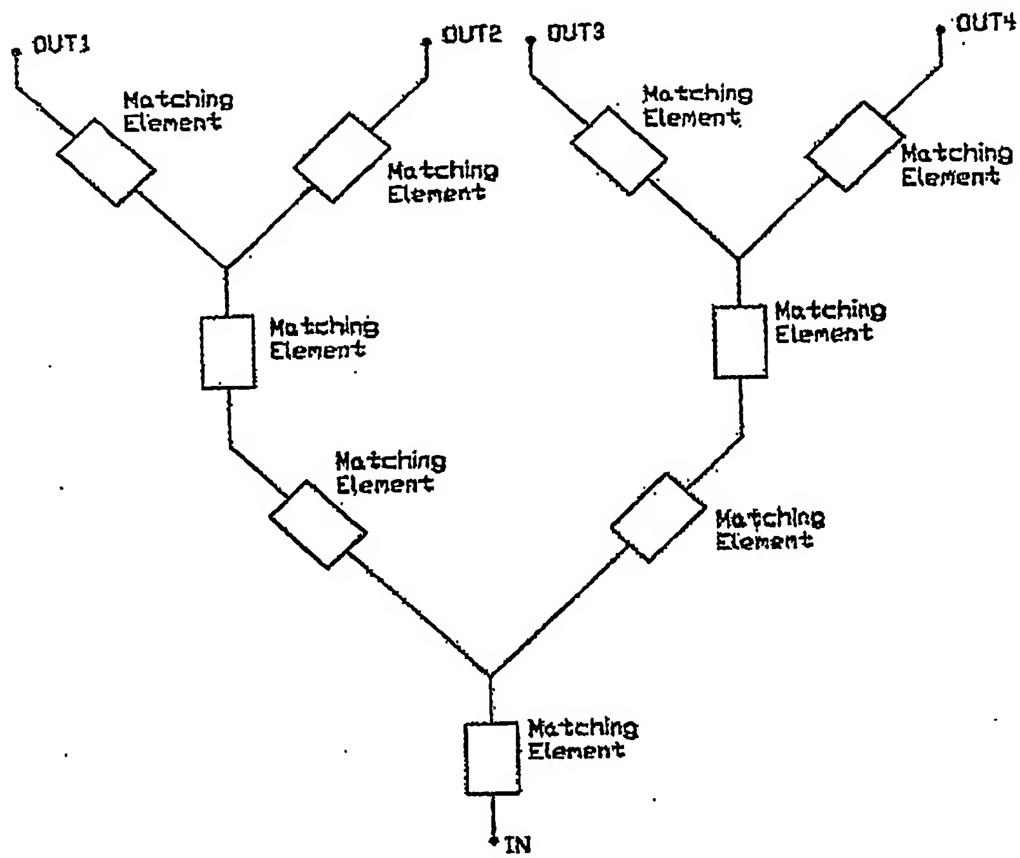



*Fig. 5.3: RF splitter block diagram.*

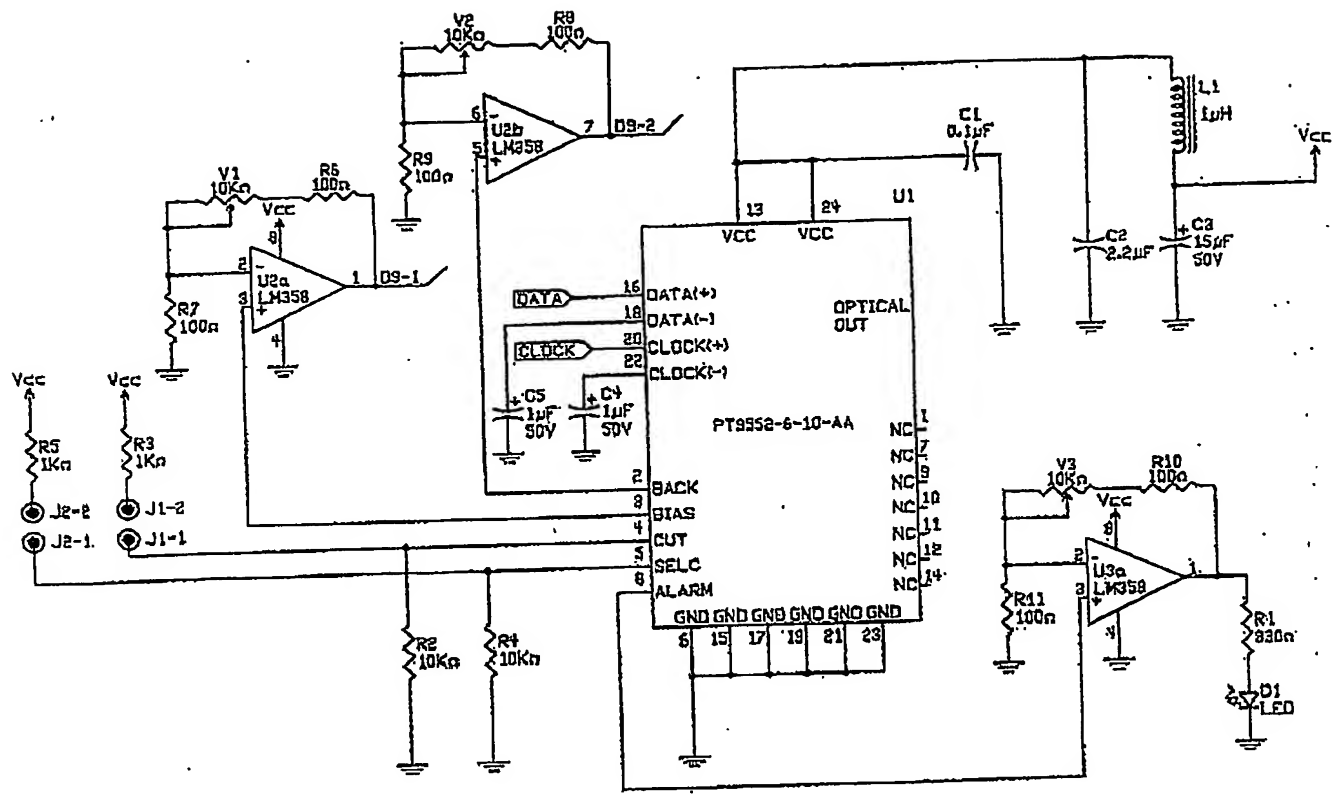



Fig. 5.4: Transmitter Laser board electric diagram.

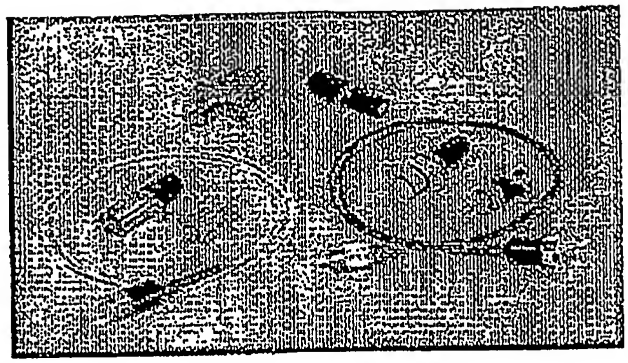


Fig. 5.5: The beacon laser, PD-LD Inc. PL83 series.

FRONT PANEL

REAR PANEL

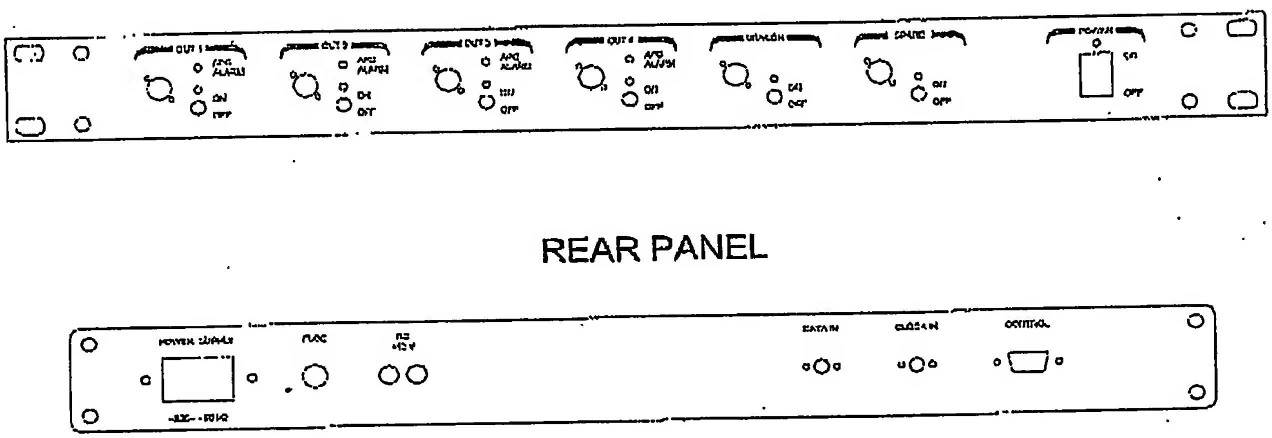


Fig. 5.6: Transmitter case front and rear panel.

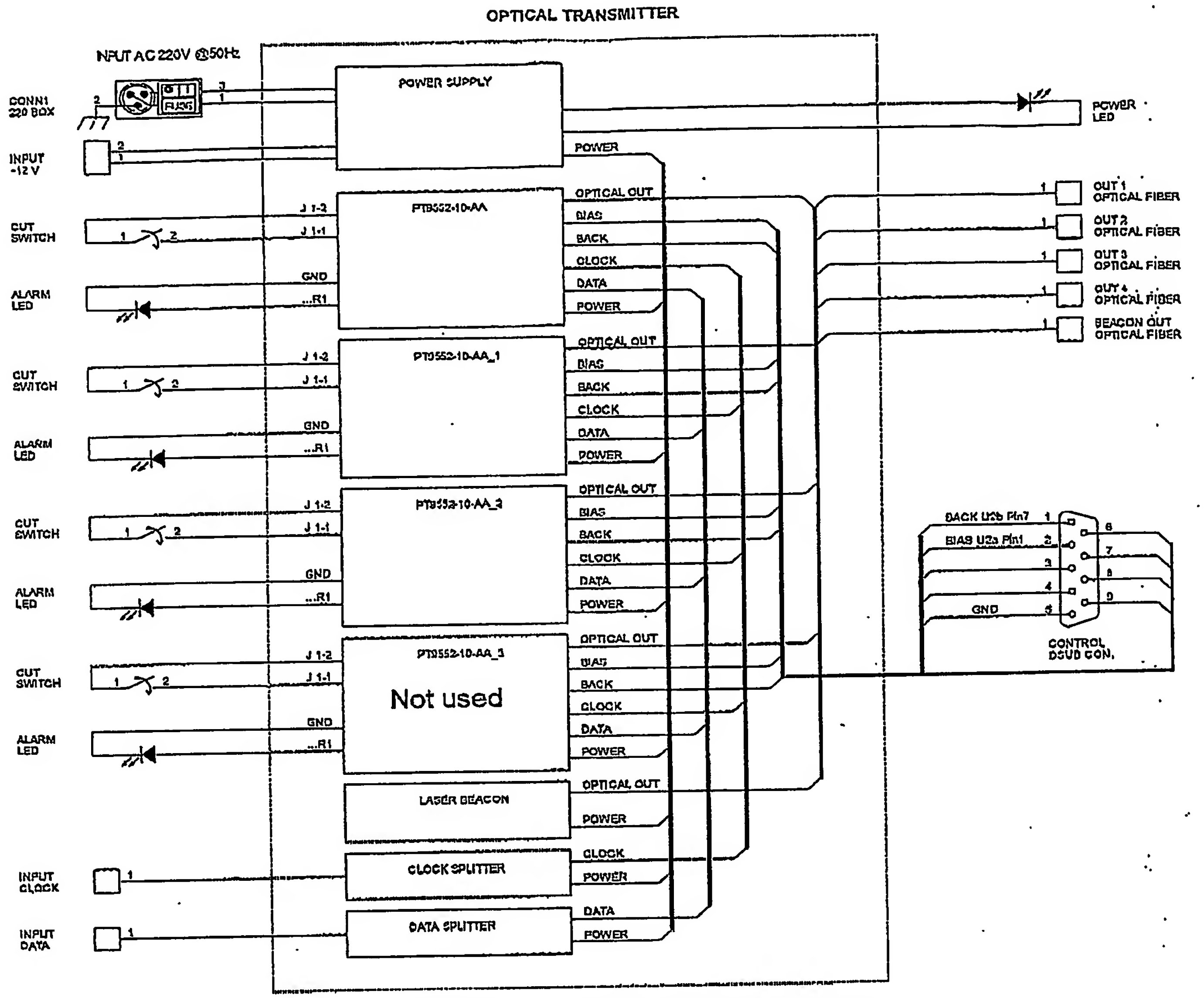



*Fig. 5.7: transmitter indoor unit internal cabling.*

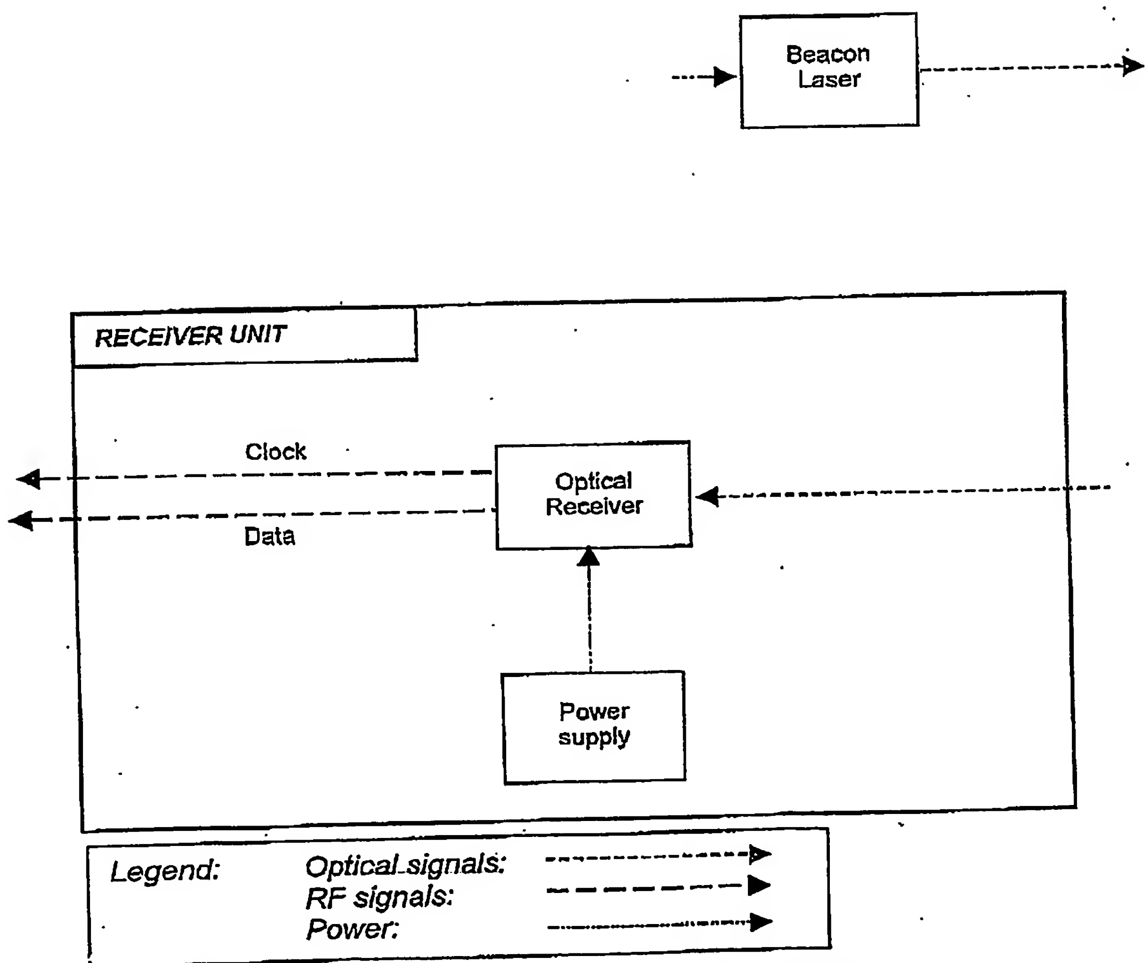



Fig. 5.8: Receiver functional block diagram.

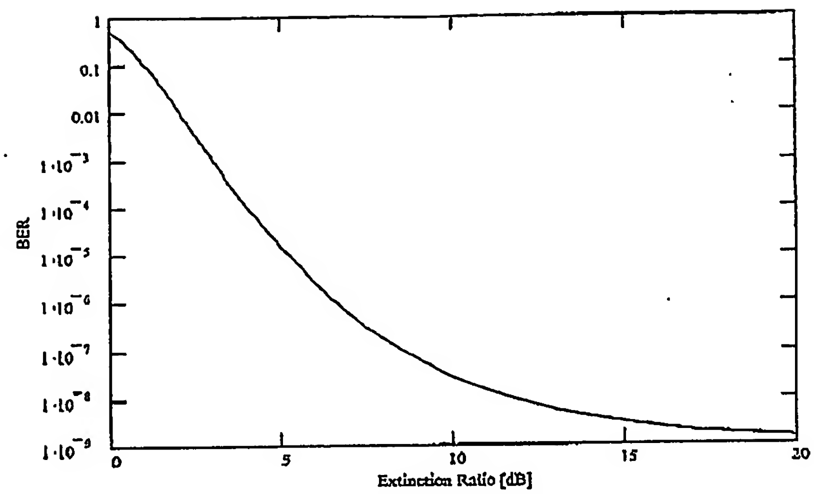



*Fig. 5.9. BER as a function of the extinction ratio at –25 dBm peak received power.*

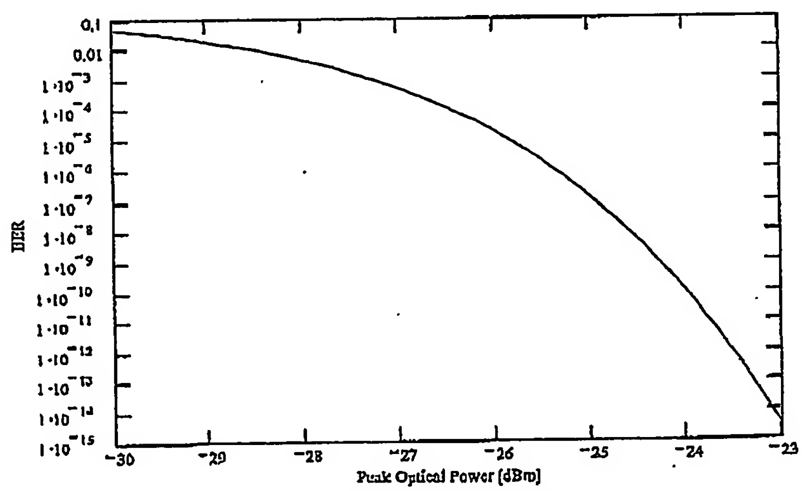



*Fig. 5.10. BER as a function of the peak received power at 8.2 dB extinction ratio.*

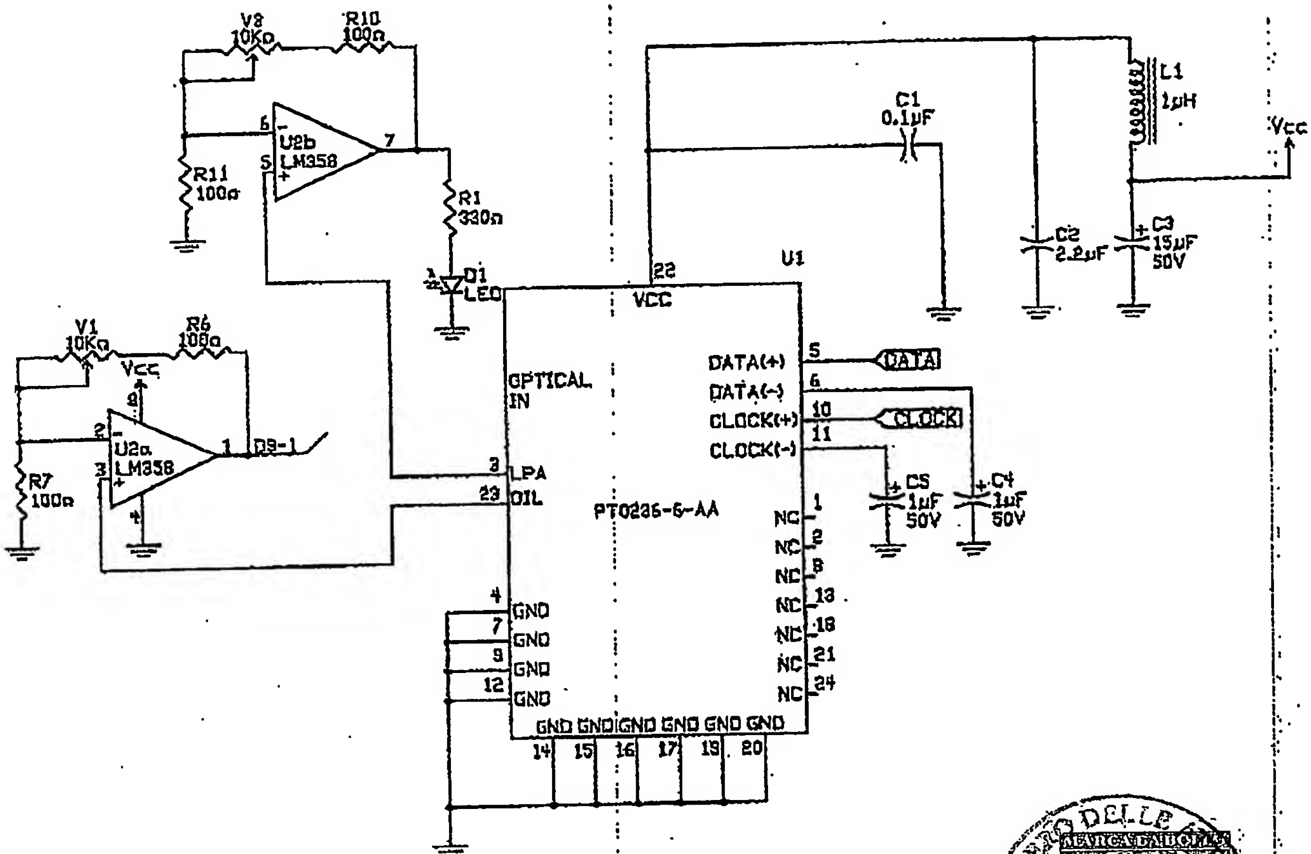
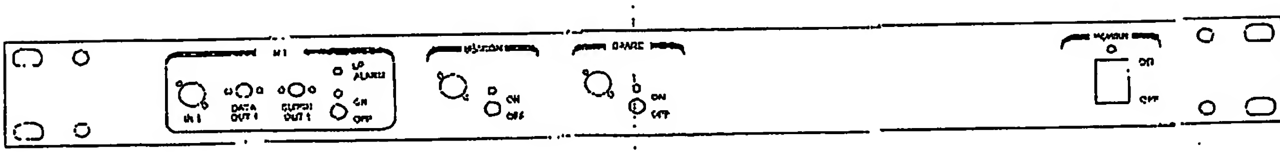



Fig. 5.11: Receiver board electric diagram.

FRONT PANEL




REAR PANEL

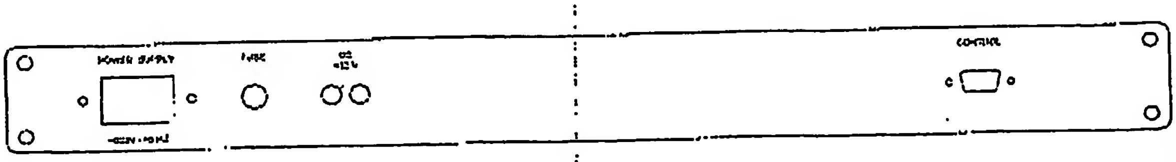


Fig. 5.12: Receiver case front and rear panel.

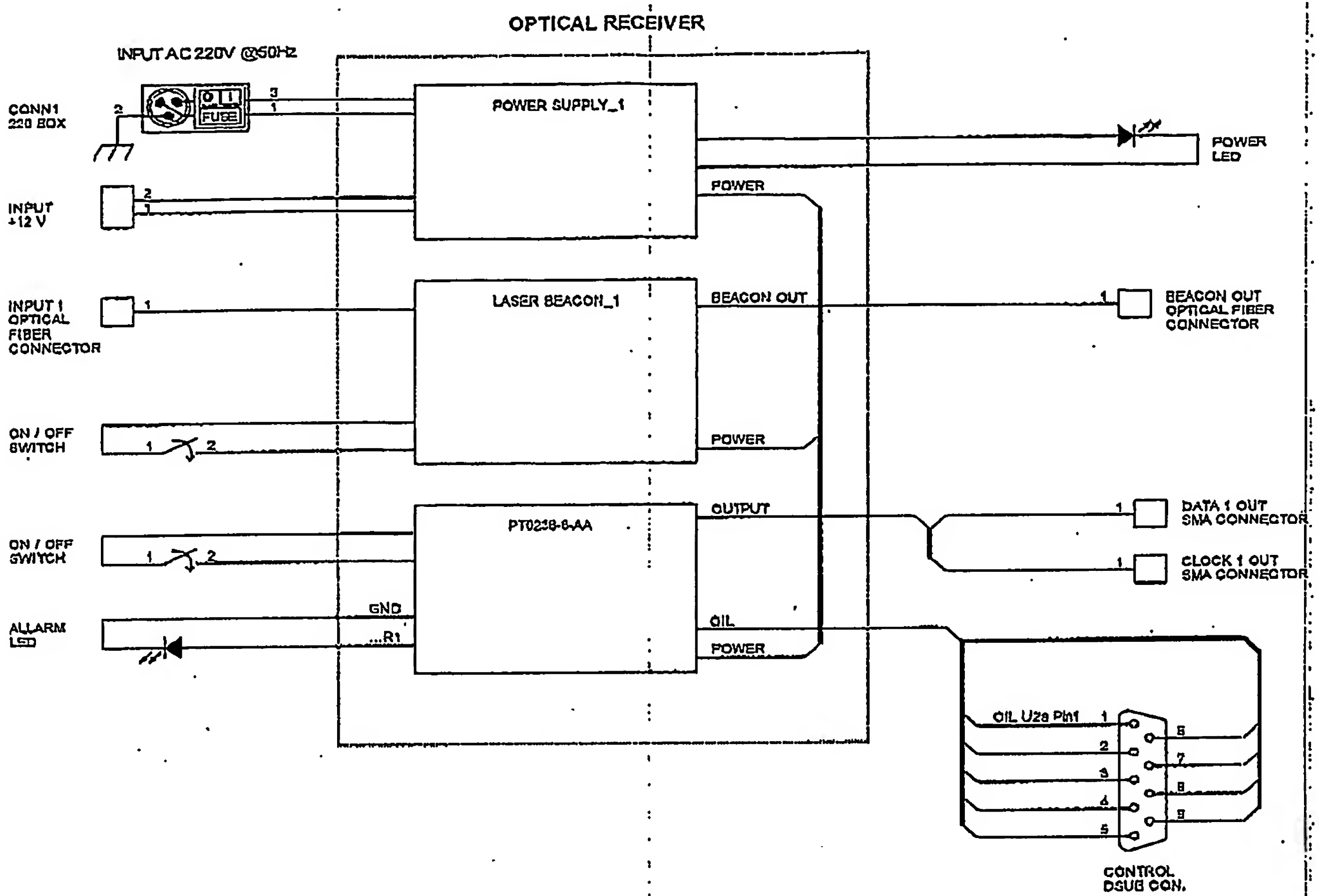



*Fig. 5.13: Receiver indoor unit internal cabling.*

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